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Isotopic composition of lead white pigments on qeros: implications for the chronology and production of Andean ritual drinking vessels during the colonial era

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Abstract
For millennia, qeros have been a primary component of ceremonially and politically important toasting rituals in the Andes and retain their cultural significance to this day. These wooden drinking vessels underwent a stylistic and technical revolution in the colonial period (1532–1821 AD). Among an array of features that distinguish colonial qeros from their Inka predecessors is the presence of lead white, a pigment that was introduced to the Andes by the Spanish. Here, we present lead (Pb) isotope measurements of lead white pigments from 20 colonial qeros from the collections of the National Museum of the American Indian, the American Museum of Natural History, the Brooklyn Museum of Art, the Metropolitan Museum of Art, and in a private collection. Although most of the vessels are not known to be associated with one another, their lead white pigments fall into three distinct and internally consistent groupings in Pb isotope space. We interpret the isotopic signatures of two of the groups to indicate that the lead white was imported from Europe. We suggest that the largest grouping (comprising pigments sampled from 12 qeros) is decorated with lead white of Andean origin. These isotopic signatures may have a chronological component, and strongly suggest some form of centralization in pigment acquisition, manufacture, and/or distribution in the colonial period.

Keywords: Qero, Colonial, Andes, Inka, Lead white, Pb isotopes, Provenance

Introduction

Ceremonial drinking vessels have been produced and used for toasting rituals in the Andes for millennia. Inka vessels made of gold or silver are called aquillas. Inka and colonial period vessels made of wood used for this purpose are called qeros, a Quechua word that means both cup and wood. These vessels were fabricated and used in nearly identical pairs to make ceremonial toasts expressing reciprocal social, political, and religious relationships [1]. Spanish chroniclers documented the important role of qeros in Inka culture [2] and their inclusion in legal documents such as wills attests to their importance as heirlooms and indicators of identity throughout the colonial period [3–5]. Qeros are still used today and have become a recognized symbol of the Inka Empire and the persistent traditions carried out by descendants of the Inka [6, 7].

Qeros were made by and for Andean communities, and represent one of the most important forms of indigenous artistic expression during the colonial period (1532-1821 AD) [8]. Notably, the decoration and designs found on

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colonial qeros are radically different from those of their Inka predecessors. The surfaces of Inka qeros are incised with regular, repeated abstract geometric designs such as chevrons, zigzag lines, and *tocapu*, modular motifs such as concentric rectangles. In contrast, colonial qeros may combine the Inka-style geometric designs with figural motifs (typically fauna and flora) or human figures [1, 3, 9]. In addition, many colonial vessels are decorated with elaborate pictorial scenes that portray human figures in archaic imperial Inka dress, sometimes in combination with figures in attire signifying certain ethnic groups from Inka times or in European clothing. Other scenes depict Inka ritual ceremonies in which qeros were used [8]. Some colonial qeros incorporate European motifs such as dragons, mermaids, and heraldic symbols. The designs of colonial qeros signify both the rapidly changing social dynamics of the colonial period and the persistence of Inka traditions and identities amid these changes.

Because they provide a window into the Andean indigenous colonial experience, qeros have been extensively studied by art historians, archaeologists, and anthropologists [1, 6, 9]. Scholars have put forth numerous ideas about the importance and role of qero imagery in the colonial era. For example, Flores Ochoa et al. [10] describe the role of qeros and qero imagery as a form of native resistance to colonial rule. Cummins [1] emphasizes that while qeros were commodified as part of the colonial economy, the imagery "transcended the intrusive colonial aspects of production to have resonance within the communities where [they] were used and seen." In another view, Martínez [11, 12] maintains that the images and designs that cover the surfaces of colonial qeros were a system of communication that preserved social memory by recording aspects of the Andean conceptual and symbolic universe. Ziólkowski [13] asserts that qeros were used by indigenous elites to confirm and legally legitimize their social rank, based on Inka ancestry, in colonial society. We may never fully know the meanings of qeros for native Andeans at this time, but as many indigenous forms of art and expression were severely curtailed by the Spanish, the visual language preserved on qeros is important to understanding the cultural ramifications of the tumultuous transition from the Inka to the colonial era.

Given this importance, there have been considerable efforts to interpret the motifs and themes depicted on qeros in the context of the times and places in which they were produced. However, it remains difficult to assign dates to qeros made during the colonial period and little is known of the artists who created these objects or where their workshops were located. While the corpus of systematically excavated Inka and pre-Inka wooden vessels has increased since the late 19th and early 20th centuries [14–17], most colonial qeros now in museums and private collections not only lack provenience but also have poor collections provenance records. Thus, there are few means of establishing the age or origin of these vessels based on their collections histories. Notably, radiocarbon analyses of wood have provided broad constraints on the ages of some qeros, but the meaning of these ages is uncertain due to several factors including the use of wood from long-lived trees and the possibility that artisans used or reused "old wood" in their manufacture [3].

Because limited chronological information can be obtained from either historical sources or isotopic dating methods, our current understanding of when specific qeros were made relies largely upon stylistic analyses of surface decoration, manufacturing techniques, and morphology. Various scholars have proposed relative chronologies for colonial qeros based on these factors [1, 10, 18, 19], but there is some question regarding whether certain stylistic developments occurred sequentially or simultaneously [1]. In addition, because colonial qeros display limited variability in size, shape, style, and iconography, some have argued that there must have only been a few workshops or locations where the vessels were made [1]. Although some scholars have proposed specific centers of qero manufacture based on either stylistic [12] or archival evidence [1, 4], the identification of particular production centers or areas remains speculative.

Qero polychromy in the colonial period

This study is part of the growing body of work [3, 20–26] that applies a materials-based perspective to understanding the production of colonial qeros. Several well-documented technical shifts in qero decoration took place during the colonial period. These include the use of a wide variety of pigments and the proliferation of a complex technique for applying polychrome inlays to the incised designs. While it is speculated that some Inka qeros may have been colored, no such qeros have yet been identified in a securely Inka context. In contrast, colonial qeros are decorated with a variety of mineral-based pigments, synthetic inorganic compounds, and natural dyestuffs [3, 21–24, 26]. These include orpiment and pararealgar for yellows and browns, cinnabar and cochineal for reds and pinks, and indigo for blues [23, 26]. Greens were created by combining indigo with pararealgar/orpiment, or by using copper-based minerals and materials, including malachite, brochanite, and possibly verdigris [23, 26]. Lead white was commonly used for pure white and in mixtures with other colorants, although a small subset of colonial qeros have an unusual white pigment containing cristobalite, anatase, and α-quartz [3]. Notably, this titanium/silica-based white pigment appears only on qeros that are considered to be "early colonial" by other scholars based on style and has therefore been proposed as a possible chronological marker for qeros made in the earliest part of the colonial period [3]. It appears the use of this pigment was soon replaced by lead white as a result of Spanish influence [3].

The pigments were inlaid into incised designs with a unique binder, a processed resin harvested from plants of the genus *Elaeagia,* commonly called mopa mopa [24, 27]. Prehispanic antecedents of this resin-based polychrome are unknown, but are believed to have originated in the Pasto area of southwestern Colombia, where the plant is found today and where *Elaeagia* resin is still used in the manufacture of folk art [5, 20, 28–30]. Although the use of many of the colorants and materials (including mopa mopa) found on colonial qeros are known or suspected to have been used for other artworks in Inka times and before, this sophisticated resin-based polychrome technique undergoes a florescence in the colonial period for reasons that are not well understood [24].

Lead white pigments

Although many of the pigments decorating the surface of colonial qeros have a long history of use in the Andes, lead white was not used prior to the colonial period. In general, the term "lead white" refers to pigments that have a lead carbonate base, which is usually either cerussite ($PbCO_3$), hydrocerussite ($(PbCO_3)_2(OH)_2$), or a mixture of the two [31]. Although Inka and pre-Inka groups are known to have used lead metal and lead-copper alloys [32, 33] there is no evidence that they ever made or used lead-based pigments. Instead, white pigments found on prehispanic Andean wall paintings, ceramics, and sculptures generally contain gypsum, calcite, or clays [34–37]. Lead white not only appears on colonial qeros, but has also been identified on 16th century sculptures [38, 39] and many colonial paintings from the Andes [40–46]. It was also used in combination with mopa mopa resin in a related colonial art form known as *barniz de Pasto*, produced in Pasto, Columbia and Quito, Ecuador for the Spanish market (see Additional file 1 for further details on white pigments found on *barniz de Pasto* objects).

The appearance of lead white on Andean objects during the colonial period was almost certainly the result of Spanish influence. The earliest European painters arriving in Cuzco brought with them technical expertise derived from a longstanding tradition of manufacturing artificial lead white pigments [45]. Lead white has been produced and used across Europe since antiquity and was described by scholars such as Theophrastus [47] and Pliny [48, 49]. There are many known historical recipes for synthesizing lead white, a process by which metallic lead is oxidized to lead carbonate compounds (generally cerussite or hydrocerussite) using reactions between lead metal, acetic acid, oxygen, and carbon dioxide [31, 50]. Cerussite and hydrocerussite also occur as minerals, although their naturally occurring forms have historically been used rarely as pigments.

In the early years of the Spanish Viceroyalty in Peru, written documents provide direct records of Spanish imports of lead white, along with other pigments, to the Americas. In a notable example [45, 51], one of the *Libros reales de Potosi* (Royal Books of Potosi), which records levies of sales tax between 1597 and 1625, counts "ceruse of Seville" (lead white) among goods to be valued for taxation. In addition, Siracusano [45] and Lewin [51] cite a manuscript from the first half of the 17th century written by an anonymous Portuguese merchant, entitled "Inventory of all the kinds of merchandise that are necessary for Peru and without which they cannot manage, since they are not manufactured in the land," which names lead white in its extensive list of goods.

Here, we investigate the origin of the lead white pigments applied to colonial qeros by measuring their lead (Pb) isotope compositions. The large natural variation of Pb isotope ratios among ore deposits combined with the preservation of primary source signatures in processed or extracted materials make Pb isotopes extremely useful indicators of provenance. Indeed, Pb isotopes have been used in archaeology for well over six decades to identify or constrain the sources of many types of artifacts including metals, minerals, ceramics, and pigments (for a partial history of the use of Pb isotopes in archaeology, see Killick et al. [52]), and have also been applied to objects in cultural heritage and art historical studies. In particular, the Pb isotope composition of lead white paints has been used to discern the sources of lead white used by European artists from medieval times through the 20th century [53–57] and for investigating the authenticity of paintings with uncertain attributions [57, 58].

When applied to colonial qeros, Pb isotopes can help distinguish between lead white pigments imported from Europe versus those produced from local Andean ores. However, isotopic measurements can potentially provide insights beyond provenance. Isotopic differences among qeros may not only reveal distinct sources of lead white on these vessels, but also could potentially be used to track the manufacture of qeros in different production centers or track shifts in pigment sources through time. By investigating the source(s) of these lead white pigments, we seek to contribute to a broader understanding of both the manufacture and chronology of these ritual vessels in the colonial period.

Methods

Samples

We analyzed lead white pigments removed from 20 colonial qeros that currently reside in the collections of the National Museum of the American Indian (NMAI), the American Museum of Natural History (AMNH), the Brooklyn Museum of Art (BMA), the Metropolitan Museum of Art (MMA), and in a private collection (Table 1). Pictures of a subset of these objects are given in Fig. 1, but images of all qeros from this study are provided in Additional file 2. Using information available in the published literature, we have compiled the dates associated with specific vessels (based on either stylistic characteristics or radiocarbon dating) in Table 2. Details of the radiocarbon dating on one of the qeros (Private Collection A) have not been previously published and are provided as additional files (see Additional file text, Figs. S1 and S2 and Table S1 in Additional file 3). Two of the qeros in our sample set (BMA 64.210.2 and BMA 36.356) are a pair. Although many of the qeros had lead white pigments in multiple design elements, for most of the objects, pigment was removed from one spot on each vessel. However, one of the qeros (AMNH 41.2/516) had two spots sampled (Table 1). Because successful Pb isotope analysis typically only requires between about 5 to 50 nanograms (ng) of Pb, the amount of material needed is minimal; our samples were about the size of a grain of sand or smaller. Samples of this size contain more Pb than needed for analysis, do not result in readily discernible damage to the object, and are large enough not to be lost during handling or sample preparation.

Table 1 Isotopic ratios of lead white on qeros

Museum ID	$^{208}Pb/^{207}Pb$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Group 1 (European source inferred)					
AMNH B9165[a]	2.0968	1.1726	18.376	15.671	38.531
BMA 36.356	2.0971	1.1725	18.375	15.672	38.533
NMAI 06/5838	2.0969	1.1726	18.374	15.670	38.529
Average	2.0969	1.1726	18.375	15.671	38.531
2 SD	0.0002	0.0001	0.001	0.002	0.004
Group 2 (European source inferred)					
AMNH B9180[a]	2.0852	1.1790	18.422	15.625	38.414
BMA 64.210.2	2.0869	1.1775	18.414	15.639	38.429
BMA 1993.2	2.0867	1.1773	18.409	15.637	38.413
MMA 1994.35.13	2.0865	1.1773	18.411	15.638	38.414
Private collection A	2.0850	1.1798	18.435	15.626	38.436
Average	2.0861	1.1782	18.418	15.633	38.421
2 SD	0.0017	0.0023	0.021	0.014	0.021
Group 3 (Andean source inferred)					
AMNH B1848[a]	2.0727	1.1929	18.666	15.648	38.690
AMNH 41.2/516 -spot 1	2.0731	1.1912	18.632	15.640	38.625
AMNH 41.2/516 -spot 2	2.0728	1.1915	18.635	15.640	38.624
AMNH 41.2/602	2.0724	1.1916	18.631	15.636	38.610
AMNH 41.2/7659A	2.0727	1.1915	18.633	15.638	38.618
BMA 42.149	2.0721	1.1920	18.643	15.642	38.633
MMA 1994.35.25	2.0722	1.1921	18.644	15.639	38.635
MMA 1994.35.26[a]	2.0726	1.1915	18.634	15.639	38.621
NMAI 06/5837	2.0727	1.1916	18.635	15.637	38.624
NMAI 10/5636	2.0726	1.1917	18.633	15.637	38.617
NMAI 16/6131	2.0730	1.1914	18.634	15.640	38.627
NMAI 17/5445	2.0730	1.1913	18.631	15.640	38.622
Private collection B	2.0725	1.1915	18.632	15.638	38.615
Average	2.0726	1.1917	18.637	15.640	38.628
2 SD	0.0006	0.0009	0.019	0.006	0.040

[a] Average of duplicate measurements

Fig. 1 Examples of qeros from each isotopic grouping identified in this study. **a** AMNH B9165; **b** BMA 1993.2; **c** NMAI 17/5445. Isotopic measurements suggest that the lead white pigments on qeros in panels (**a**) and (**b**) are of European origin while those on the qero in panel (**c**) are derived from an Andean source. The qeros in panels (**a**) and (**b**) have been attributed to the late 1500 s or early 1600 s on the basis of style [19, 77] while the qero in panel (**c**) has been attributed to the 1700 s [1]

Table 2 Qero ages based on stylistic chronologies and isotopic methods

Museum ID	Published chronologies	^{14}C ages/Calendar age range*
Group 1 (European source inferred)		
AMNH B9165	Late 16th century [19]	
BMA 36.356		
NMAI 06/5838		
Group 2 (European source inferred)		
AMNH B9180		
BMA 64.210.2	Late 16th to 17th century [77]	
BMA 1993.2	Late 16th to 17th century [77]	
MMA 1994.35.13	Early to mid-17th century [78]	
Private collection A		Resin: 180 ± 15 ^{14}C years BP 1671-1923 cal years AD Wood: 300 ± 15 ^{14}C years BP 1513–1664 cal years AD
Group 3 (Andean source inferred)		
AMNH B1848		
AMNH 41.2/516	Late 17th to early 18th century [1]	Wood: 185 ± 30 ^{14}C years BP** 1666–modern cal years AD
AMNH 41.2/602		
AMNH 41.2/7659A		
BMA 42.149	Late 17th to 18th century post-1630 AD [19]	
MMA 1994.35.25		
MMA 1994.35.26	Late 17th century [78]	
NMAI 06/5837	18th century [19]	
NMAI 10/5636		
NMAI 16/6131		
NMAI 17/5445	18th century [1]	
Private collection B		

*Radiocarbon ages were calibrated using Oxcal v. 4.3 [79] and the SHCal13 atmospheric curve [80]. Details of the radiocarbon dating of resin and wood from "Private Collection A" are given in Additional file 3

**The ^{14}C age on AMNH 41.2/516 was reported in Cooke et al. [81]

Lead isotope analysis

The isotopic measurements were made using an IsoProbe multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) in the Department of Geosciences at the University of Arizona. The samples were dissolved in an ultra-pure nitric acid (HNO_3) solution and then diluted to Pb concentrations of ~ 25 ppb in a 0.1 M HNO_3 matrix for analysis. Analytical protocols follow those presented in Thibodeau et al. [59]. All results were normalized to values reported by Galer and Abouchami [60] for the National Institute of Standards and Technology standard reference material 981 (NIST SRM 981).

Errors were calculated from the external reproducibility of NIST SRM 981 over the course of each measurement session. Errors (2 SD) were ~ 0.01% for $^{207}Pb/^{206}Pb$ and $^{208}Pb/^{206}Pb$ ratios; ~ 0.02% for $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios; and ~ 0.03% for $^{208}Pb/^{204}Pb$ ratios. Four sample solutions were measured twice to check reproducibility, and, in these cases, the average ratios are reported (see Table 1). Errors calculated from the reproducibility of individual sample solutions were smaller than errors calculated from the external reproducibility of NIST SRM 981. Analytical blanks contained < 100 picograms of Pb, which is many orders of magnitude smaller than the quantity of Pb in each sample solution.

Results

The qeros can be divided into three groupings based on the isotopic signatures of their lead white pigments (Table 1; Figs. 1, 2 and 3). These groupings are apparent on bivariate plots no matter which Pb isotope ratios are chosen (Fig. 2). For simplicity of discussion, we label these groups 1-3 in ascending order of their mean $^{206}Pb/^{204}Pb$ ratios: Group 1 has a mean $^{206}Pb/^{204}Pb$ ratio of 18.375 ± 0.001 (2 SD, n = 3), Group 2 has a mean $^{206}Pb/^{204}Pb$ ratio of 18.418 ± 0.021 (2 SD, n = 5), and Group 3 has a mean $^{206}Pb/^{204}Pb$ ratio of 18.637 ± 0.019

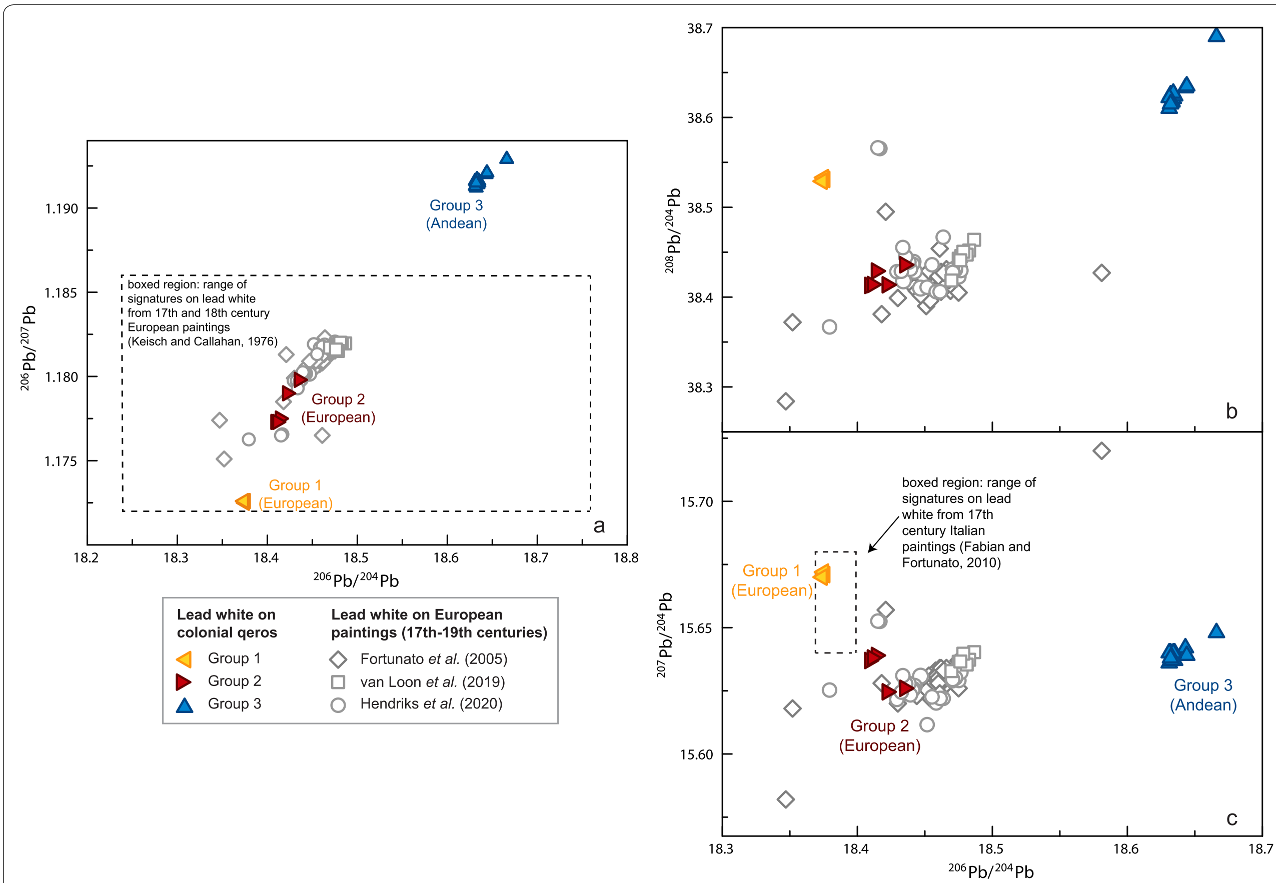

Fig. 2 Lead isotope composition of lead white pigments from colonial qeros and lead white paints from European paintings. Note that pigments in Groups 1 and 2 overlap with signatures of lead white paints from 17th-19th century Europe, but that pigments in Group 3 do not. See text for further explanation. Note that Keisch and Callahan [57] and Fabian and Fortunato [64] do not provide isotopic signatures of individual paintings, but instead report the ranges of isotopic ratios measured on groups of paintings. Accordingly, we depict these signatures as regions using only the specific isotopic ratios provided by each study. Symbols are larger than errors. Data on European lead white paints were compiled from refs [53, 54, 63]

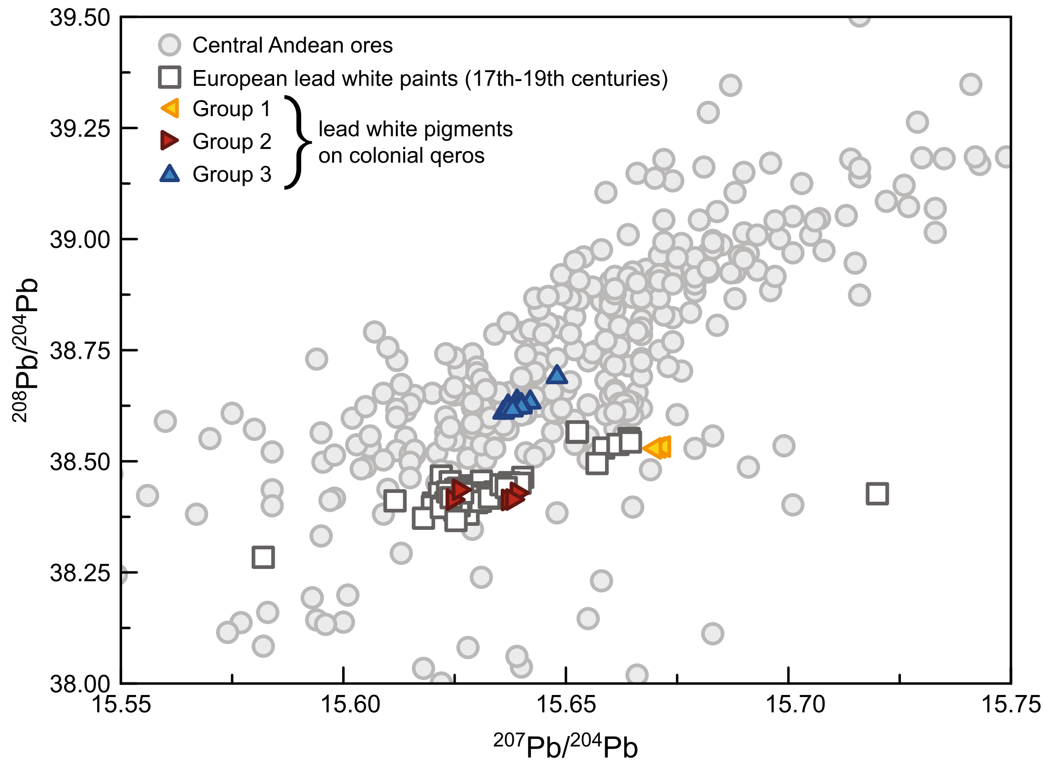

Fig. 3 Lead isotope composition of central Andean ores, European lead white paints, and lead white pigments from colonial qeros. Although lead white pigments from Groups 1 and 2 plot within the range of isotopic signatures measured on Andean ore deposits, they coincide extremely well with the specific ranges of Pb isotope ratios that characterize contemporary European lead white paints. Thus, we suggest they derive from European and not Andean sources. In contrast, pigments in Group 3 have isotopic ratios that not only separate them from European lead white paints, but also that are very typical for ores in the central Andes (compare to data in Macfarlane and Lechtman [62], see text for additional discussion). Ore data were compiled from refs [62, 66–69]. Data on European lead white paints are the same as displayed in Fig. 2. Symbols are larger than errors

(2 SD, n = 13) (Table 1). The majority of the qeros in this study (12 of 20) fell into Group 3. The two qeros in our sample set that form a pair (BMA 64.210.2 and BMA 1993.2) have lead white pigments with matching isotopic compositions (Table 1). In addition, the two discrete lead white samples taken from one of the qeros (AMNH 41.2/516) have isotopic ratios that are identical within analytical error (Table 1).

Discussion

Origin of the lead white pigments used on colonial qeros

It is notable that the qeros cluster into only three relatively "tight" groupings in Pb isotope space (Figs. 2 and 3). With the exception of the one pair within our sample set, the qeros in this study are not known to be associated with one another either spatially or temporally. It is therefore intriguing that their lead white pigments display such limited isotopic variation.

Notably, the isotopic signatures of the three qeros in Group 1 are identical within our measurement errors. There is slightly more spread among qeros in Groups 2 and 3, but in each case, the clustering is still extremely tight. For example, if we exclude AMNH B1848 from the 12 qeros represented in Group 3, the spread in $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios among the objects is only about twice the magnitude of the analytical error (at the 2σ level) or less. Regardless, the very small scatter among ratios within Groups 2 and 3 is still well within the variation that can be expected in natural sources. The preservation of just three signatures across twenty qeros suggests that the acquisition, preparation, and/or use of lead white by Andean artists was likely centralized or limited in some way. This uniformity not only indicates that qeros within each grouping likely share a common geologic source of lead white, but also could be interpreted as evidence that the same batch of lead white pigment was used to decorate many of the vessels within each group.

Given that Pb isotopes vary widely in nature on both small and large spatial scales, a limited number of geological sources are represented by the pigments in our sample set (for recent reviews on how geological constraints impact the Pb isotope systematics of ore deposits, see Albarède et al. [61]; Macfarlane and Lechtman [62]; and Killick et al. [52]). Usually, determining the geologic provenance of a material, such as pigment, would entail comparing it to possible ore sources from which it could have been derived. However, not only is there a large number of lead-bearing ore deposits in both the Andes and Europe but there is also substantial overlap in the Pb isotope compositions of non-ferrous mineral deposits from these two regions of the world (for compilations of Pb isotope data from each region, see Killick et al. [52]). Thus, without a means of narrowing candidate ore deposits within the Andes or Europe, it is not possible to unambiguously determine the origin (Andean vs. European) of the lead white pigments by comparison to geological materials alone (see Fig. S3 in Additional file 4).

Fortunately, other existing Pb isotope data provide the opportunity for a more strategic approach to discerning the provenance of the pigments in this study. These data derive from lead white paints associated with European art created from the 16th through early 19th centuries [53, 54, 57, 63]. Thus, to evaluate the possibility that colonial qeros were decorated with lead white imported from Europe, we do not rely on simple comparisons to ore data. Instead, we directly compare our results to the Pb isotope ratios of lead white paints present on contemporary (late 16th–early 19th century) European artwork.

Several studies have examined the isotopic composition of lead white paints used in Europe at this time. The first and most comprehensive of these was undertaken by Keisch and Callahan [57] who measured the isotopic ratios of more than 400 samples of lead white from European and American works of art spanning the 13th to 20th centuries. Unfortunately, they did not directly publish most of these data, but instead summarized them in a series of tables and figures [57]. In one of their summary tables, they report the range of isotopic ratios measured on these artworks according to the century in which they were produced. Their results clearly show that, during the 17th and 18th centuries, lead white used by European artists had a limited range of isotopic compositions (Fig. 2a). Although they do not provide a list of the paintings analyzed, their sample set from these two centuries includes 82 samples from Dutch (including Flemish and Belgian), English, German, Italian, and Spanish works of art.

Although Keisch and Callahan [57] do not, for the most part, report the isotopic ratios measured on individual paintings, there are more recent isotopic studies of lead white paints that do. These studies report Pb isotope ratios measured on lead white from paintings created by 17th century Flemish and Dutch artists [53, 63] as well as 18th and 19th century British and Swiss artists [54]. Notably, the studies are broadly consistent with one another (Fig. 2a–c), and all the isotopic data they contain fall within the range of signatures originally proposed by Keisch and Callahan [57] (Fig. 2a). The limited isotopic variation observed in European paintings created over several hundred years has been explained by citing the large-scale production of lead white in the Netherlands and Great Britain during the 17th, 18th, and early 19th centuries and the likely use of British ores in both production centers at that time [54].

Irrespective of the exact ore deposits used, these previous characterizations of European lead white paints provide a basis to evaluate the provenance of lead white pigments applied to colonial qeros. Pigments in two of the groupings (Groups 1 and 2) have isotopic ratios that are consistent with a European provenance. In particular, pigments in Group 2 are especially similar to 17th, 18th, and 19th century lead white paints from Europe [53, 54, 63] in all dimensions of lead isotope space (Fig. 2 and Fig. S4 in Additional file 5). The isotopic ratios of pigments in Group 1 are slightly offset from the main cluster of 17th–19th century European lead white paints in Fig. 2, although they still fall within the bounds proposed by Keisch and Callahan [57]. Intriguingly, the signature of the pigments in Group 1 may match that of lead white used in 17th century Italy. Although they do not provide a table of data, Fabian and Fortunato [64] report that lead white paints on a group of 17th century Italian paintings have $^{206}Pb/^{204}Pb$ ratios between 18.37 and 18.40 and $^{207}Pb/^{204}Pb$ ratios from 15.64 to 15.68 ($^{208}Pb/^{204}Pb$ ratios are not given) (Fig. 2c). These signatures align well with qeros in Group 1 (Fig. 2c). An Italian origin for the lead white pigments in Group 1 is plausible given historical evidence that Italian traders were important suppliers of lead white to multiple regions of Spain, particularly in the 16th century [65]. Thus, it is possible that pigments in Group 1 were imported to the Andes from Spain relatively early in the colonial period.

Overall, there is an excellent match between the lead white pigments in Groups 1 and 2 and contemporary European lead white paints. However, we note that the isotopic ratios of Groups 1 and 2 also overlap with some ore deposits within the Andes (Fig. 3). Despite this overlap, it is doubtful that these pigments were made from Andean lead. The range of isotopic signatures found on European lead white paints is quite small relative to Andean ore deposits (Fig. 3). Further, as shown in Fig. 3, there are relatively few isotopic measurements of Andean ores that actually coincide with the signatures of pigments in Groups 1 and 2 (and the European lead-white paints) (see Fig. S4 in Additional file 5 for alternate visualizations of these data). Based on these observations, it seems highly unlikely that the isotopic correspondence between European lead white paints and pigments in Groups 1 and 2 is purely coincidental, especially in light of historical evidence for the import of European lead white to the Andes during the colonial period [45, 51]. Based on the totality of evidence, we strongly favor the interpretation that qeros in Groups 1 and 2 are decorated using lead white imported from Europe.

Unlike Groups 1 and 2, lead white pigments in Group 3 have isotopic signatures that diverge significantly from the large corpus of European lead white paints (Figs. 2 and 3). Comparison with Andean ores [62, 66–69] reveals that the signatures of these pigments coincide well with geological materials in the Andes (Fig. 3). Based on these observations, we suggest these pigments derive from an Andean source. Unfortunately, we cannot identify a specific source for the lead because the isotopic composition of pigments within Group 3 is not unique to ore deposits in any one region of the Andes. Indeed, if we compare Group 3 pigments to the Pb isotope provinces proposed by Macfarlane and Lechtman [62] for the central Andes, the isotopic signatures of the pigments are consistent with multiple geographic regions. The similar Pb isotope signatures of many ore deposits across western South America can be attributed to the fact that many ore deposits are of similar age (Cenozoic), formed through similar processes, and share the same tectonic setting [52, 62].

If the pigments in Group 3 are Andean in origin, as we suggest, there are several possibilities for how they were produced; they could have been made by indigenous Andeans using native metallurgical technologies or using techniques learned from Europeans. Pigment could also have been obtained from Europeans with the expertise to produce it locally. One intriguing prospect is that Andean artists could have made lead white not through the corrosion/oxidation of lead metal (as was standard practice in Europe at the time), but by using natural deposits of cerussite, as suggested by Tomasini et al. [39], citing the possible use of natural cerussite in a priming layer on a late 16th century polychrome sculpture made by Andean native Francisco Tito Yupanqui. Although the isotope analyses presented in this study cannot reveal the technical aspects of lead white production, our evidence for an Andean origin for the lead white on many colonial qeros raises new questions about how indigenous artisans adopted and perhaps eventually produced a pigment originally of Spanish introduction.

Implications of Pb isotopes for qero production and chronology

If both European and Andean lead white were used on colonial qeros, as we suggest based on the Pb isotope data, these findings have several important implications for our understanding of these vessels. Although placing the qeros investigated here into a relative chronology based on stylistic/iconographic/morphological attributes is beyond the scope of this study, it is possible that these isotope data record a chronological shift, with Andean artists initially using European lead white and then incorporating pigment manufactured from an Andean source starting at a later date.

It seems likely that the earliest examples of lead white pigment are of European origin given the body of work documenting European import and the absence of this pigment in the Andes prior to the colonial period. Further, we note that this interpretation is not contradicted by the previous placement of some of these qeros within published stylistic chronologies. For example, at least some of the qeros decorated with European lead white have been attributed to the earlier part of the colonial period based on style (Table 2). These include the pair of qeros within Group 2 (BMA 64.210.2 and BMA 1993.2) and at least one of the vessels (AMNH B9165) in Group 1. In contrast, many of the qeros decorated with what we suggest is Andean lead white have been assigned late 17th or 18th century dates by stylistic chronologies (Table 2). Characteristics thought to be typical of the "later" colonial period include decoration with elaborate pictorial scenes and the use of a broad palette of colorants [21]. Additionally, some of the qeros within Group 3 are footed (e.g., NMAI 17/5445 and AMNH B1848, see Fig. 1 and Additional file 2), another trait thought to appear during the later colonial period (Thomas Cummins personal communication, 2020). Although a possible chronological aspect to the data is intriguing, we do not have enough information to determine when Andean lead white first appeared, or to discern if imported European pigment continued to be used to some extent throughout the colonial period. Thus, our goal is not to propose specific usage dates for European vs. Andean lead white, but only to suggest the potential for a temporal component to the isotopic signatures found here.

Even if there were a temporal component to the usage of European and/or Andean lead white, pigments bearing these three distinct Pb isotope signatures must have been used over relatively long periods of time. One possibility is that the isotopic groupings identified in this study could be related to specific sites where qeros were produced. Although there are no known records or descriptions of the workshops where qeros were made, many scholars have noted that there is a strong consistency in figural style, iconography, vessel size, technical style, and materials used during the colonial period [1]. Further, the polychrome inlay technique (utilizing mopa mopa as a plant resin binder) is a complex, multi-step process requiring specialized knowledge and experience [5, 22, 24, 26–28, 70–76]. Based on broad similarities among vessels, Cummins [1] suggests that there were probably just a few centers devoted to the production and distribution of qeros in the colonial Andes. He identifies one of these centers as La Plata (modern day Sucre, Bolivia), an important city on the trade route between La Paz and the silver mine at Potosí [1]. Martínez et al. [12] also suggest a limited number of production centers based on distinct local indigenous experience in the colonial era, reflected in style: the Cusco region, Omasuyos-Lake Titicaca, and Charazani.

If there were only a few production centers for colonial qeros, the limited variation in the isotopic signatures of lead white in each group may reflect the long-term use of particular lead sources or pigment batches by specific centers of production. For example, individual workshops may have acquired different batches of lead white imported from Europe and then used those batches for significant lengths of time. This could explain the presence of two distinct "European" signatures in our dataset. Alternatively, imported batches of lead white could have been distributed or shared among production centers, leading to similar isotopic signatures among qeros made in different workshops.

The uniformity of isotopic signatures among qeros with Andean lead white (Group 3) indicates that these objects are almost certainly decorated with lead white from a common geological source or conceivably a common batch of pigment. If the vessels were not all made in the same workshop, it is possible that batches of prepared pigment (or the raw materials to make it) were shared/distributed among production centers.

Conclusions

We have identified three isotopic signatures on 20 colonial qeros from the Andes. The isotopic evidence suggests that over the colonial period, indigenous artists used both lead white imported from Europe and lead white derived from Andean ores. The identification of three distinct pigment sources may be related to either spatial or temporal factors. Although it is not clear when an Andean source first came to be used, it is very likely that the earliest examples of lead white pigment on qeros used materials imported from Europe. The limited isotopic variation among a group of vessels not known to be directly related supports the idea that there were a limited number of centers where qeros were produced and may imply the sharing or controlled distribution of prepared pigment batches, raw materials, or both.

Because this type of isotope analysis requires very little material, there should be few barriers to investigating a larger number of vessels to test whether the present study has characterized the full extent of isotopic variation present in lead white pigments applied to colonial qeros. Lead isotope ratios will be most informative when combined with other forms of evidence, such as stylistic analysis, to test ideas about the spatial and temporal components of qero production. In addition, it would be useful to investigate the isotopic composition of lead white on other pieces of contemporary Andean artwork to see if similar materials and shifts can be identified across other mediums.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s40494-020-00408-w.

Additional file 1. Use of white pigments on *barniz de Pasto* objects.

Additional file 2. Images of colonial qeros.

Additional file 3. Radiocarbon dating of wood and resin from a colonial qero residing in a private collection ("Private Collection A").

Additional file 4. Lead isotope compositions of lead white pigments from colonial qeros compared to Andean and European/Mediterranean ores.

Additional file 5. Isotopic comparison of central Andean ores, 17–19th century European lead white paints, and lead white pigments from colonial qeros.

Abbreviations

AD: Anno domini; common era; NMAI: National Museum of the American Indian; AMNH: American Museum of Natural History; BMA: Brooklyn Museum of Art; MMA: Metropolitan Museum of Art; MC-ICP-MS: Multi-collector inductively coupled plasma mass spectrometry; NIST SRM 981: National Institute of Standards and Technology Standard Reference Material 981; AMS: Accelerator mass spectrometry; BP: Before present, indicates conventional radiocarbon age; SD: Standard deviation; ppb: Parts per billion.

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Authors' contributions

EK, EH, EP and JL conceived of the original project and contributed object images and samples for analysis. AT supervised the analytical work and AC prepared the samples, performed the isotopic measurements, and processed the data. AC and AT interpreted the data, wrote the main body of the text, and created the figures. EK contributed the cultural and art historical background and gathered object images. EK and EH made significant contributions to the text. All authors read and approved the final manuscript.

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Availability of data and materials

All data generated or analyzed during this study are included in this published article [and its supplementary information files].

Competing Interests

The authors declare that they have no competing interests.

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