Technical Analysis and Identification of a Glass Inlaid Sui-Tang Dynasty Woman's Crown

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Abstract

A woman's crown made of fine gilt bronze with refined glass inlay work was excavated in 2007 from the Sui-Tang tomb called Kunlun M2 in Xi'an. Many questions surround this mysterious crown which was found buried without context. This study uses nondestructive analysis of the crown to determine its significance, when it was made, and the status of the woman for whom it was made. Optical microscopy (OM), optical coherence tomography (OCT), micro X-ray fluorescence imagery (XRF), and Raman spectroscopy were applied, and identified the crown's inlays as potash-lime glass, composed mainly of the raw materials include vein quartz or quartzite with potassium nitrate as flux. The inlays were sintered before embedding into gilt copper wire filigree. Compared with existing research on other crowns and their inlays, it is speculated that the crown dates from the Sui dynasty (581-618) or early Tang dynasty (618-649), was made locally by Chinese craftsmen and belonged to the wife of an official.

1 Introduction

In January 2007, the Xi'an Kunlun Industry Company found two tombs at their premises in an eastern suburb of Xi'an. That month, the Xi'an Institute of Cultural Relics Protection and Archaeology conducted a rescue excavation of the tombs. A large number of crown ornaments were discovered in the M2 tomb. Archaeological investigation and research classify M2 as a typical tomb of the Sui dynasty (581-618) to early Tang (618-649) dynasty, with such ritual female crowns belonging to the late Sui and early Tang periods. There is a lack of archaeological information to further identify the Kunlun M2 crown (such as an epitaph tablet), but scientific research helps to explore the intrinsic chemical character of the crown's decorative elements and manufacturing techniques used, as well as placing it in the context of technological developments and exchange, and social significance in the Sui-Tang period.

The crown was made using filigree inlay, a technique that originated in the Warring States Period (475-221 BCE), when it was called jin yin cuo (gold and silver inlay) and involved painting gold and silver onto the surface of bronze artworks. By the Sui and Tang dynasties, filigree inlay technique was mature, with the development of high level techniques for making fine gold and silver thread. Examples of exquisite ornamented female crowns include that of Sui dynasty Empress Xiao (566-648, wife of Emperor Yang), and the Tang dynasty 'phoenix crown' found in the 736 tomb of the royal family member Li Chui (Fig. 2). Tang dynasty women's crowns were also recorded in the incised line drawings on the interiors of the stone sarcophagi in the Qianling tombs of Crown Prince Zhanhuai and Crown Prince Yidu, dating from 706. The filigree technique in the Kunlun M2 crown is not as elegant as these, however. This suggests that the owner of this crown was not of the highest status, though without epitaph tablets or other identifying information extant in the tomb, her precise status is difficult to ascertain. This paper analyses the physical evidence of the inlay materials and the way these were combined with the base metal to unlock more historical information about the crown. Thus, we can combine the inlays' physical and chemical information together with the typology of the crown to identify the status of crown's owner more accurately, while shedding new light on the inlay techniques of the Sui-Tang period.

2 Nondestructive Analysis Methodology

Due to the Kunlun M2 Crown's rarity, elite character and significance as a cultural relic of Chinese national importance, destructive methods of analysis were not permitted. Accordingly, OM, OCT, microfocus XRF and Raman spectroscopy were used to analyze the ornament samples of the Kunlun M2 crown, OCT was used for the first time in China for high-resolution imaging of inlays, and microfocus XRF (not commonly used in archaeological analysis), with its highly focused beams of light, allowed precise control of the areas to be tested and accurate data to be obtained in seconds. The parts that were analyzed are shown in Fig. 3.

2.1 Description of samples

Figure 1 shows five parts of the Kunlun M2 crown after conservation. The main color on the headpiece is green coated with gold and colourful, elegant, and sumptuous decorations. BB-1 and BB-2, called bo bin (broad sideburns), were distributed on both sides of the head, lower than the ears simulating sideburns or streamers (Fig. 4-a). Granulated bronze beads at the periphery of these elements began to evolve under the influence of Sasania (Persia) during the Northern and Southern Dynasties, and became typical inclusions in crown designs of the Sui-Tang period, reaching a peak in the Tang Dynasty (Fig. 4-c). Apricot leaf-shaped ornaments, XY-2, XY-3, XY-6, XY-8, would have hung at the back of the crown; these are called bao dian (filigree inlay) (Fig. 4-c). Typically, the size and materials of bo bin and the number of bao dian represent the class of the person who wore the crown. In Fig. 4-b, there is a flower bouquet-shaped decoration called bu yao (an ornament that quivers when the wearer walks). The bu bin, bao dian, and bu yao together could form a floral female crown popular in the Sui-Tang dynasty. Bu yao quivering pieces, were also found in Kunlun M2, but are not analyzed in-depth in this article. In total, excavation of M2 revealed two bo bin, eight bao dian, and the remains of at least four bu yao pieces, indicating that the Kunlun crown belonged to a high-class woman. Crowns of the highest rank consist of twelve bao dian, so the owner of the Kunlun M2 crown, with eight bao dian, could be the wife of a second-grade official (not less than an Imperial Chief Secretary or an Imperial General).

Each part of the headpiece has extensive inlays with granulated metal beads surrounding them. The inlay materials and their associated manufacture technique are little known due to the small number of Sui-Tang female crowns or headwear discovered so far, and because most of these are too rare and precious to be subjected to destructive analysis. Of known crowns, the Kunlun crown is most similar in type to that of Sui dynasty Empress Xiao (566-648, wife of Emperor Yang) excavated in Yangzhou, Jiangsu Province in 2012, and the earliest empress' crown discovered thus far. Both the M2 Kunlun crown and Empress Xiao's crown are made of gilt bronze, with multiple inlays, bo bin, bu yao, and bao dian, as well as coherent beads at their periphery.

2.2 Instrumental techniques

The discovery of the Kunlun M2 crown has enabled the conduct of the analytical experiments in this study to observe and analyze the inlays, using OM, OCT, XRF, and Raman with the following test conditions:
The microscope used in this experiment was made by the ZEISS company, Germany, connected to a tablet computer equipped with Matscope software to obtain relatively clear micrographs. In Table 1, the magnification of these images is 100 times.

**OCT**

Optical coherence tomography (OCT) is the optical analog of ultrasound imaging and is emerging as a powerful imaging technique enabling non-invasive, high resolution, cross-sectional imaging in light transmittable material. Its axial resolution is typically 3µm to 15µm, and the imaging depth in the air is typically 2mm.

**Microfocus XRF**

The microfocus X-ray fluorescence spectrometer used was a model artax-400, made by BRUKER, Germany. The range of elements analyzed was 11Na – 92U (the content of sodium was not measured in the actual experiment, as the error margin would have been too large), and the spatial resolution was 0.2-1.5mm, better than 159eV. During the experiment, there was an Rh target, and the beam spot diameter was 1µm.

**Raman spectroscopy**

This experiment was tested using laser microscopy with a confocal Raman spectrometer (model In Via, Reinshaw, Co., Ltd.). The excitation wavelength of the Ar ion laser source is 532nm, the spectral range is 200nm – 1060nm, and the spectral resolution is 0.5 – 1cm – 1. During the experiment, the temperature generally required is between 18°C and 30°C, with the humidity below 50%.

### 3 Results

#### 3.1 Micrographs of the Kunlun M2 crown headpieces

<table>
<thead>
<tr>
<th>XY-2 A</th>
<th>XY-2 B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gilt copper wire filigree and brown inlay</td>
<td>Gilt copper wire filigree and transparent inlay</td>
</tr>
<tr>
<td>XY-2 01</td>
<td>XY-2 02</td>
</tr>
<tr>
<td>Gilt copper wire filigree and blue inlay</td>
<td>Gilt copper wire filigree and yellow inlay</td>
</tr>
<tr>
<td>XY-2 03</td>
<td>XY-8 H</td>
</tr>
<tr>
<td>Gilt copper wire filigree and inlay adhesive</td>
<td>Gilt copper wire filigree and blue inlay</td>
</tr>
<tr>
<td>XY-8 G</td>
<td>BB-2 04</td>
</tr>
<tr>
<td>Gilt copper wire filigree and turquoise inlay</td>
<td>Inlay impurities</td>
</tr>
<tr>
<td>BB-2 05</td>
<td>BB-2 06</td>
</tr>
<tr>
<td>Inlay impurities</td>
<td>Pearl-like inlay</td>
</tr>
</tbody>
</table>

### 3.2 OCT results of the Kunlun M2 crown inlays
Table 2. OCT results of the Kunlun M2 crown inlays

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample</th>
<th>OCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>XY-2</td>
<td></td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>A</td>
<td>Semi-transparent brown inlay</td>
<td>Approx. 0.4mm thickness, with surface coat and cracks inside</td>
</tr>
<tr>
<td>XY-2</td>
<td></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>B</td>
<td>Transparent inlay</td>
<td>About 0.7mm thickness, with no surface coat but cracks inside</td>
</tr>
<tr>
<td>No.</td>
<td>Sample</td>
<td>OCT</td>
</tr>
<tr>
<td>XY-8</td>
<td></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>H</td>
<td>Opaque blue inlay</td>
<td>Thickness cannot be detected</td>
</tr>
<tr>
<td>BB-2</td>
<td></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>J</td>
<td>Opaque dark blue inlay</td>
<td>Uneven surface</td>
</tr>
<tr>
<td>BB-2</td>
<td></td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td>L</td>
<td>Opaque white inlay</td>
<td>Thickness cannot be detected</td>
</tr>
</tbody>
</table>

### 3.3 Focal XRF of Kunlun M2 crown inlays
4.1 Characterization of the decorative pieces

4.1.1 Surface topographical features

A magnification of 50, reveals numerous bubbles and cracks in the inlaid decorative materials (XY-2 01, XY-2 02, XY-8 H), and these contain obvious impurities (BB-2 04, BB-2 05). Inside the gilded copper forming the frames of the decoration there is an unknown white substance that seems to be binding material for the inlays (XY-2 A, XY-2 B, XY-2 03, XY-8 G). Pearls form a circular decoration around the edges of the headpieces, (BB-2 pearl). The inlays are colorful but the inlay workmanship on the headpieces overall is not finely executed, with the individual inlay frames uneven in width and lacking uniformity of shape (XY-2 01, XY-2 02). There is a conchoidal fracture on the transparent inlay of XY-2B. In BB-2 05 there is an uncommon characteristic, where it appears that gold foil is embedded within the inlaid decorative material; possibly an accidental inclusion of gold foil that has fallen into the raw material of the inlay. Other impurities are also evident in the inlays (BB-2 04).

All surface topographical features reveal rough workmanship, and the inlaid materials are in an amorphous state, full of bubbles. To understand the techniques and materials used to make the inlays, OCT was used to observe the internal features of the inlays. The results are shown in Table 2.

4.1.2 Optical coherence tomography (OCT) features

OCT is a well-used tool for the inspection of reverse glass painting (Hinterglasmalerei, 背面彩繪) paintings, faience, jade and porcelain in the field of Heritage Research[17–22], as it is a fast non-contact and non-invasive technique for the examination of objects that consist of transparent or semi-transparent materials. In this study, all samples with a thickness from 50 µm to 100 µm have a “surface coat”. This may have been caused by weathering and could have affected the composition of the materials, therefore the surface coats were removed to exclude disturbance to the analysis. The OCT image of sample B, reveals damage to the inlay in the form of a crack (see Table 2-B). Due to the lack of comparable OCT data from other ancient glass artifacts from the Sui-Tang dynasty, it is not possible to ascertain its relative quality and sophistication of craftsmanship.

### Table 3

<table>
<thead>
<tr>
<th>Sample</th>
<th>Type</th>
<th>Color</th>
<th>Dynasty</th>
<th>Place</th>
<th>concentration (Wt-%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Si</td>
</tr>
<tr>
<td>XY2-A</td>
<td>insertC</td>
<td>brown</td>
<td>Late Sui</td>
<td>Xi'an</td>
<td>34.82</td>
</tr>
<tr>
<td>XY8-E</td>
<td>insertC</td>
<td>dark blue</td>
<td>Late Sui</td>
<td>Xi'an</td>
<td>89.69</td>
</tr>
<tr>
<td>XY8-F</td>
<td>insertC</td>
<td>brown</td>
<td>Late Sui</td>
<td>Xi'an</td>
<td>78.86</td>
</tr>
<tr>
<td>XY8-G</td>
<td>insertC</td>
<td>green</td>
<td>Late Sui</td>
<td>Xi'an</td>
<td>88.55</td>
</tr>
<tr>
<td>XY8-H</td>
<td>insertC</td>
<td>blue</td>
<td>Late Sui</td>
<td>Xi'an</td>
<td>95.77</td>
</tr>
<tr>
<td>BB-K</td>
<td>insertC</td>
<td>yellow</td>
<td>Late Sui</td>
<td>Xi'an</td>
<td>33.17</td>
</tr>
<tr>
<td>BB-J</td>
<td>insertC</td>
<td>blue</td>
<td>Late Sui</td>
<td>Xi'an</td>
<td>95.03</td>
</tr>
<tr>
<td>BB-3</td>
<td>insertC</td>
<td>green</td>
<td>Late Sui</td>
<td>Xi'an</td>
<td>89.43</td>
</tr>
<tr>
<td>BB-I</td>
<td>insertC</td>
<td>yellow</td>
<td>Late Sui</td>
<td>Xi'an</td>
<td>66.78</td>
</tr>
</tbody>
</table>

3.4 Raman spectrum of XY-8 of the Kunlun M2 crown

3.5 Principal Component Regression (PCR) and Principal Component Analysis (PCA) of Chinese potash-lime glass

The chemical composition of Chinese potash-lime glass is shown in the appendix. Its PCA is as follows:

4 Discussion

This study is the first to analyze glass inlays in a crown. These tests can contribute to knowledge more widely about glassware and help with the study of crowns and other inlaid objects.
4.2 Material composition

After examining the optical characterization of the inlays, their composition was analyzed using micro focal XRF and Raman.

4.2.1 Elemental composition

Table 3 summarizes the analysis of the composition of the decorations on the M2 crown using micro focal XRF. The test results of XY2-A and BB-K were affected by the base metal. Most of the Silicon (Si) content ranges from 66.78 to 95.770 wt%, the content of only XY2-A and BB-K are lower than 34.82wt% and 33.117wt% respectively, potassium (K) content ranges from 0.33 to 7.46, most calcium (Ca) content ranges from 1.92 to 10.32, and only BB-L shows 21.47wt% which is several times that of other decorations, with ferrum (Fe) content ranges from 0.17 to 1.18 wt%. It is important to note that aluminum (Al), magnesium (Mg), and sodium (Na) are not present in these samples, while sulfur (S) abounds in XY2-A and BB-K and there is a small quantity in XY-F and BB-L.

This chemical composition as a whole indicates that the inlays are potash-lime glass. Soda lime silicate glass which was introduced to China from the West has been made and applied in Inner China since the Tang Dynasty. Na$_2$CO$_3$, NaNO$_3$, and CaCO$_3$ are more common minerals in Western glass and some of the domestic Chinese glass.$^{[24-34]}$. High potassium content is not typical of Western glass but is characteristic of Central and Southeast Asian glass$^{[35,36]}$, and research work has demonstrated that the ratio of silicon to potassium of China's potassium glass is higher than other Central and Southeast Asian countries.$^{[34,37]}$. The inlaid glass sample in this paper has elemental characteristics consistent with domestic Chinese glass.$^{[24,38-41]}$.

According to modern glass scientific research, potassium silicate glass has the characteristics of higher chemical stability, is not easily crystallized, and has material enhancements making it suitable for the manufacture of more complex glassware of exquisite appearance.$^{[42,43]}$.

The high amount of silicon and lack of aluminum indicate the use of raw material excluding arenaceous quartz and sandstone, and probably including vein quartz or quartzite. Arenaceous quartz contains a small number of impurities such as Al$_2$O$_3$, K$_2$O, Fe$_2$O$_3$, FeO, Cr$_2$O$_3$, and TiO$_2$, they all can be used to make glass coloring and affect its transparency. Sandstone is a kind of clastic sedimentary rock formed by cementing quartz particles and cementing material under high pressure. The cementing material can be divided into clay sandstone (containing more Al$_2$O$_3$), arkose sandstone (containing more K$_2$O), and calcareous sandstone (containing more CaO). The appearance of sandstone is mostly yellowish and reddish, and red when iron staining is strong. The variation range of SiO$_2$ content is 65%-95%.

Vein quartz is an igneous rock with a hard texture and sedimentary crystalline Properties. Its appearance is pure white and translucent with a greasy luster. It fractures like a shell and has a SiO$_2$ content of up to 99%. Quartzite is a metamorphic rock, which is formed by the recrystallization of quartz grains by the metamorphic process of siliceous sandstone. Its SiO$_2$ content is more than 97%, it is hard and not easy to crush, and is a good raw material for manufacturing ceramics and advanced glass products.

The presence of K and absence of Mg might indicate the use of saltpeter (potassium nitrate) as a fluxing agent rather than plant ash, with Ca being the stabilizer of the admixture. According to Fuxi Gan "Development of glass technology in ancient China", about the Northern Song dynasty (960-1127), to further improve the physical properties of glass, saltpeter (KNO$_3$) was generally used as a flux, so that K$_2$O replaced part of the PbO, and changed lead silicate glass to potassium and lead silicate glass.$^{[44]}$. Based on archaeological typology, the "bead circle line" (Fig. 3) on the objects from this experiment belong to the late Sui or early Tang dynasty.$^{[45]}$

Saltpeter, straw ash, and potash fertilizer are discovered as the source of most potassium elements used to make potassium calcium silicate glass in ancient China. It is not clear whether saltpeter was used in the production of glass in Sui Dynasty, but there was certainly no use of straw ash or potash fertilizer in the raw material of Kunlun M2 woman's crown.

4.2.2 Composition of the inlays

In Fig. 6a, XY-8e is the Raman spectrum of the base metal of XY-8, with peaks of 902.571cm$^{-1}$, 1012.21cm$^{-1}$, 1336.94cm$^{-1}$, 1444.15cm$^{-1}$, and 1554.36cm$^{-1}$. The grey inverted triangles indicate that all Raman spectra have the similar peaks compared to XY-8e, at around 900cm$^{-1}$, 1100cm$^{-1}$, 1300cm$^{-1}$, 1335cm$^{-1}$, 1420cm$^{-1}$, 1445cm$^{-1}$, 1551cm$^{-1}$. The base metal has a significant effect on the Raman test results of glass inlays, so the possible molecular structure of the glass inlays' composition is still unknown.

In Fig. 6b, the Raman spectrum peaks of blue glass in the sample XY-2 are 591.093cm$^{-1}$ and 1080.050cm$^{-1}$, the Raman spectrum peaks of the gold foil of the sample XY-8 are 585.703cm$^{-1}$, 609.467cm$^{-1}$, 686.162cm$^{-1}$, 1133.359cm$^{-1}$, 1365.990cm$^{-1}$ and the Raman spectrum peaks of a pearl-like inlay on sample BB-1 are 145.968cm$^{-1}$, 202.261cm$^{-1}$, 699.009cm$^{-1}$, 1080.050cm$^{-1}$. The main composition of this inlay is calcium carbonate, which means it is highly possible that BB-2.06 is pearl.

4.3 Comparison of Chinese ancient potash-lime glass

This study has analyzed the glass inlays of the Kunlun M2 crown and shown that they are all potash-lime glass. Chinese potassium glass was not common in the Sui and Tang dynasties$^{[46]}$ and has not been systematically studied. To discover what role these potash-lime-glass decorations played in ancient China, this investigation has collected most of the representative data and compared these with the data of the glass inlays of the Kunlun M2 crown using the PCR method. The data is shown in Table 4.
In Fig. 7 the samples in Table 4 were grouped into four categories, by dynasty, excavation location, type, and color, respectively, to understand how the ratio of materials in the samples was affected. The elemental components of the glassware samples have significant regional characteristics. This could be because the ratios of materials used in local glass handicraft industries varied by production time, relic type, and their appearance of color, but were consistent by excavation place. Therefore, potash-lime glass was hypothesized to have been made locally, and the ratio of the raw material would have been decided by the local craftsmen based on experience. Unlike bronzeware, ceramics, or other mature industries in ancient China, glass manufacturing was not yet fully developed, especially potassium glass. K$_2$O-CaO-SiO$_2$ glass appeared around the Spring and Autumn period to early Warring State period (800-400 BC), mostly in the form of faience[47]. Compared with other types of glass, potassium glass has a higher softening temperature, superior toughness, and higher strength, so it is also called hard glass and is suitable for decoration making. In the Spring and Autumn period, the bronze Sword of Goujian has blue glass inlay decorations consisting of K$_2$O-CaO-SiO$_2$ glass[24, 48]. The glass was inlaid in the sword handle together with kallaite (turquoise), suggesting that K$_2$O-CaO-SiO$_2$ glass could have been one of the most valuable items indicating high honor at that time when the production of glass was probably very rare. During the historical development of glass manufacture, the value of the potash-lime glass became less as time progressed. In the Sui-Tang dynasty, the royal family used potassium glass imported from the West, but hardly used domestic Chinese potash-lime glass[21]. The Kunlun M2 crown under investigation uses potash-lime glass inlay indicating that its owner was a woman of high, but not royal, social status. According to An Jiayao’s “A Brief History of Glasswares in China”, Western glass came to China in the Han dynasty[24], and from then on Western glass gradually became a symbol of the highest status and power[21]. Domestic potash-lime glass in China, by comparison, can be taken to represent the “second highest class” up until the Song dynasty (960AD) when the glass industry was no longer under government control[21]. Exquisite domestic glassware was produced during the Sui and Tang dynasties, marking a peak of Chinese glass manufacturing[21]. Most of that domestic glass was crystal glass with a high lead content, used exclusively for vessels. After the Song dynasty, glass manufacturing in China moved from government-controlled palace workshops and temple workshops to the private sector. After that time, the value of glass began to plummet and it was no longer valued by the upper classes[21].

In the late Sui to early Tang dynasty the Kunlun M2 woman’s ceremonial crown, glass inlays were dyed to imitate crown jewels. A, E and G look similar to amber, sapphire, and kallaite, respectively. Although the overall shape of the crown has been destroyed, and the value of the domestic glass can be assessed as lower than that of precious stone, this confirms that the crown belonged to a woman of significant social status above that of an ordinary person.

4.4 Glass filigree-embedding

Two significant examples of glass inlaid products are the Spring and Autumn period bronze swords that belonged to King Fuchai of Wu and King Goujian of Yue, respectively (Fig. 8). Through scientific and technological analysis, it was found that the glass on the two sword hilts was potassium calcium silicate glass, like the Kunlun M2 crown[48].

Other examples of crowns with glass dating from the 6th and 7th centuries make significant use of the filigree technique. The 7th century Sui dynasty tomb of Shi Wushe (buried on 22 January 610), excavated in Guyuan City, Ningxia Province contained a bronze “strip” and “apricot leaf” ornaments (see Fig. 9). Shi Wushe was the Right General leading the cavalry. His ancestors came from a Sogdian city (in the present-day Republic of Tajikistan)[49]. One of the ornaments is very similar to the apricot leaf ornaments of the Kunlun M2 crown. Chen Zhonghui believes that the ornament was made with enamel technology. First, copper wire was used to make cell borders on the copper base, then the vitrified powder was placed in the cells, to be calcined with the copper forming a glass enamel. Historically, this technique, sometimes called “glass coating” inlay technology[50] was used widely from the Warring States period to the Han dynasty. In the 6th century, filigree enamel was also used on gold ornaments, such as those in the tomb of the Eastern Wei dynasty Ru Ru Princess (c.550) located north of Da Zhong Ying village, Hebei Province, and in the Northern Qi dynasty tomb of Lou Rui (c.577) in Taiyuan City (Fig. 10); Western countries also have enamel ornaments[51]. According to the archaeological record, pearls, cameolians, sapphires, emeralds, clamsheels, and glass were inlaid in the gold ornament of Lou Ru’s tomb, while pearls, gemstones, and amber were inlaid in the gold ornament of Ru Ru Princess’s tomb. None of these glass inlays were tested for composition, however[49].

In the case of the glass of Kunlun M2 crown, the base of gilded bronze is pure copper and the inlays are potash-lime glass. Comparison of the Kunlun M2 crown with the two swords of Wu and Yue, and since potassium glass is harder than other glass, it can be inferred that potash-lime glass may have been considered more suitable for inlaying. The glass transition temperature of the potash-lime glass is about 1200°C, which is higher than the melting temperature of copper which is 1083.4°C, and much higher than the firing temperature of enamel which is around 800°C. Therefore, the inlays of the Kunlun M2 crown apricot leaf ornaments must have been sintered first and then embedded inside the copper wire filigree. This is also indicated in Table 1 (XY-2A, XY-2B, XY-8H, XY-8G), where the edge of the glass inlays were not smooth, the glass was cut roughly with a conchoidal fracture, and not well matched to the ligree. Therefore, the inlays of the Kunlun M2 crown with the two swords of Wu and Yue, and since potassium glass is harder than other glass, it can be inferred that potash-lime glass may have been considered more suitable for inlaying. The glass transition temperature of the potash-lime glass is about 1200°C, which is higher than the melting temperature of copper which is 1083.4°C, and much higher than the firing temperature of enamel which is around 800°C. Therefore, the inlays of the Kunlun M2 crown apricot leaf ornaments must have been sintered first and then embedded inside the copper wire filigree. This is also indicated in Table 1 (XY-2A, XY-2B, XY-8H, XY-8G), where the edge of the glass inlays were not smooth, the glass was cut roughly with a conchoidal fracture, and not well matched to the filigree. There is also a white substance in the gap between the glass and filigree. Infrared spectroscopy, Transmission X-ray diffraction were used to analyze the composition of the white substance, but only SiO$_2$ was found.

4.5 Comparison with other crowns

Dating back to the Han Dynasty, crowns were first developed only for men to confirm their high status[54], while women use the number of _bu yao_ and _bao dian_ to distinguish status levels[8, 13]. The full coverage ceremonial crown originated during the Northern and Southern Dynasties (420-589), and only could be worn by an empress or empress dowager, while others could only use hair accessories such as _bao dian_ ((filigree inlay) and hair clasps. The complete crown was first recorded in the Northern Wei, relief sculpture of the Binyaing Middle Cave of the Longmen Grottoes[55].

In the Longmen relief, there are three crowns but only two of them are _have bo bin_. _Bo bin_ can be seen at the bottom of the crown of Northern Wei Empress Wenzhao and the presumed Queen Mother Hu, where the top of the crown looks like a lotus in full bloom and there seem to be three circular ornaments hanging from the forehead, believed by archaeologists to be leaf-shaped decorations[55].
There is a further crown with similar apricot leaf ornaments to that of Kunlun M2 unearthed from the Northern Wei Dynasty fresco tomb M1 in Chen Village, Datong, Shanxi Province. M1 is a well-preserved, high-level, and large-scale brick chamber tomb, however, due to the lack of epitaph tablets, it is impossible to know the identity of the tomb owner. Due to the lack of parts, it is also difficult to determine whether these ornaments belonged to a complete crown.

Unearthed Sui and Tang dynasty, crowns or their pieces with similar components to the Kunlun M2 crown are recorded in Table 4.

Table 4 Unearthed ceremonial crowns with bao dian, bo bin or bu yao from the Sui-Tang dynasty.

<table>
<thead>
<tr>
<th>Tomb</th>
<th>Date</th>
<th>Objects</th>
<th>Owner</th>
<th>Image</th>
<th>Number of bao dian</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern suburbs of Ningxia, Guanyan, Sui</td>
<td>610</td>
<td>bao dian and part of bi ji (髮髻) ornaments for making fake chignon</td>
<td>Shi Wuhe, Sui dynasty General</td>
<td>(Fig.9)</td>
<td>1</td>
</tr>
<tr>
<td>Shi Wuhe tomb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2 of Cao village, Yangzhou City, Jiangsu</td>
<td>648</td>
<td>A set of a complete ritual crown with two bo bin, six hairpin</td>
<td>Empress Xiao of Sui</td>
<td>(Photograph by Yang Junqiang)</td>
<td>12</td>
</tr>
<tr>
<td>province</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tang Tomb of Yan Shiwei and his wife,</td>
<td>706</td>
<td>A set of a complete ritual crown with six bao dian, humanoid, avian,</td>
<td>Lady Pei (wife of Yan Shiwei, a magistrate in Taizhou)</td>
<td>(Photograph by Yang Junqiang)</td>
<td>6</td>
</tr>
<tr>
<td>Lady Pei in Majiagou, Xi’an, Shaanxi</td>
<td></td>
<td>and floral ornaments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kunlun M2 crown</td>
<td></td>
<td></td>
<td>Unknown</td>
<td>(Fig.1)</td>
<td>8</td>
</tr>
</tbody>
</table>

Empress Xiao's crown reveals the whole scheme of a ritual crown in the Sui dynasty, combining bo bin and bao dian with bu yao (Fig.5) to form a typical ritual crown that influenced the shape of female ritual crowns until the Ming Dynasty. Together with Xiao's crown, about ten other crowns or their components have been excavated.

Xiao's crown has similar components to the Kunlun M2 crown (Fig.5 Table.4), but the inlays of its bo bin have not yet been studied. Another is the Tang dynasty crown of Lady Pei who was the wife of Yan Shiwei (magistrate of Lanxi county in Zhejiang Province) (Table 4) [59]. Yan Shiwei and his wife Lady Pei were buried in their hometown Chang'an (present-day Xi'an) on May 20 (Chinese lunar calendar) in 691. Zhang Zhengyuan identified its glass ornaments as being of two types – one is PbO-SiO₂, the other is Na₂O-CaO-SiO₂ [60], but there are no glass inlays.

Comparing the number of bao dian in the crowns of Empress Xiao and Pei, with the Kunlun M2 crown, they have twelve, six, and eight respectively. Considering the location where the M2 crown was unearthed, the owner of the M2 crown while not a royal family member, was not inferior to Lady Pei.

To date, no analysis of the inlay composition in the above crowns has been conducted, therefore systematic comparison is not possible. Future clarification of the inlays' chemical composition might enable the establishment of a classification system for Sui and Tang dynasty female ceremonial crowns. Therefore, even if only fragments of crowns can be found, important elements of the owner's personal information can be restored.

5 Conclusion

5.1 Application of OCT in glass observation
Unlike XRF, Raman detection, OCT is not a common analytical method used in archaeological research. OCT has lower environmental requirements, shorter time, simpler and cheaper instruments than CT, but for translucent and transparent materials, it works very well. In this paper, OCT could expose the cross-sectional information of glass in a nondestructive way, showing both the surface coating layers of the glass and the cracks inside.

5.2 Craftsmanship of the glass on Kunlun M2 crown

The inlays in the Kunlun M2 crown are potash-lime glass, belonging to the K₂O-CaO-SiO₂ system, and, as such, are Chinese domestic glass. This composition is not common in Sui and Tang dynasty domestic lead crystal glass. There is an undefined layer on the surface of each glass inlay, which could be a weathered layer. According to the elemental composition of the glass inlays, the raw materials of the glass might include potassium nitrate and vein quartz or quartzite. The glass inlays use lapidary techniques to cut the glass into shape and then use some additional substance to adhere them in the filigree. The whole process is fairly rough, especially on the edges of the glass and filigree.

5.3 The social status of glass products in the Sui-Tang dynasty

Glass technology was generally underdeveloped in China until it reached a peak during the Sui and Tang dynasties when glass manufacture was under government control. Potash-lime glass is one type of historical domestic Chinese glass. The ratio of chemicals comprising the glass is unique to the area and the workshop in which it was produced. It is not related to the advance of time, the particular colors, or the shape of objects. To date, no systematic data have been developed on the properties of glass at that time, nor have there been studies on the effects on the properties of glass according to the chemical distribution ratio, as is the case with historical bronze and ceramic wares. During the Sui and Tang dynasties, glass was generally used by people of the ruling class, but as the domestic glass had a lower status than imported glass, it was generally used by officials, not the royal family.

5.4 Defining the Kunlun M2 crown

The shapes of the crown's elements are very similar to those of Empress Xiao of the Sui dynasty and Lady Pei of the Tang dynasty. The base metal of all three is gilded bronze, though the inlays are different. Although the excavated parts of the Kunlun M2 crown are damaged, the extant materials used to make the crown, to some certain extent, indicate the owner's social status. Following the previous analysis, the crown was most likely produced in the late Sui or early Tang dynasty and was probably made by the royal workshop, with the female owner having a high rank in Sui or early Tang society as a member of an official family.

Declarations

Availability of data and material

The data and materials are available from the corresponding author on reasonable request.

Competing interests

All authors declare that there are no competing interests.

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Authors' contributions

Du Jingnan: Methodology, validation, investigation, data analysis, draft writing, editing and reviewing.

Tonia Eckfeld: manuscript editing and reviewing.

Yang Junchang: Project administration.

Jiang Fengrui: Project administration.

Zhang Quanmin: Provision of samples.

Shao Yanbing: Methodology, Data analyses.

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Figures

Figure 1

Extant components of the Kunlun M2 Crown (Photograph by Du Jingnan)
Figure 2
Li Chui's crown in Shaanxi Provincial Institute of Archaeology (Photograph by Liu Xingchen)

Figure 3
Ornaments of the Sui-Tang crown excavated from Kunlun M2, Xi'an, Shaanxi, China. A-L represent the test points. (Photograph by Du Jingnan)
Figure 4

Typical ornaments on Sui-Tang female crowns [8] (Drawn by Wang Fei) a. bo bin (bo), b. bu yao (bu), c. bao dian (bao)

Figure 5

Crown of Sui dynasty Empress Xiao (left) [16]; reconstructed replica of Empress Xiao’s crown (right). (Photographs by Tian Jin)

Figure 6

Crown of Sui dynasty Empress Xiao (left) [16]; reconstructed replica of Empress Xiao’s crown (right). (Photographs by Tian Jin)
a and b represent the Raman spectrum XY-8 of the Kunlun M2 crown. XY-8e is the Raman spectrum of the base metal. Other XY-8 measurements are for parts of the glass inlays, and the inverted grey triangles represent the corresponding peaks of the six measurements.

Figure 7

PCR and PCA are used in these potash-lime glass decorations to obtain statistical models that make significantly visible the samples’ chemical components and their proportional differences. (The 4 Categories – Dynasty, Place, Type and Color which were selected are the four parameters that are most likely to affect the potash-lime-glass glass composition. Dynasty and place are dependent on the samples’ sites, type is the archaeological type of the sample, color is the physical color of the glassware.)

Figure 8

a. Hilt of King Goujian’s sword. (Photograph by Gan Fuxi); b. Hilt of King Fuchai’s sword. (Photograph by Suzhou Museum)

Figure 9

The bronze strip and “apricot leaf” ornaments of Shi Wushē’s tomb, Guyuan City, Ningxia Province[49]. (Photograph by Luo Feng)
Figure 10

left. Gold ornament of Lou Rui’s tomb in Taiyuan City [52]. (Photograph by Taiyuan Institute of Cultural Relics and Archaeology); right. Gold ornament of Ru Ru Princess’s tomb [53]. (Photograph by Zhu Quansheng)

Figure 11

left. Northern Wei Empress Wenzhao’s Buddha Worship, relief sculpture (/session), Binyang Middle Cave of the Longmen Grottoes. Detail showing Empress Wenzhao[56] (Photograph by YOYO); right. Drawing of larger section showing three people wearing crowns[57]. (Drawing by Longmen Cultural Relics Depository)

Figure 12
Bronze apricot leaf ornaments of M1, Chen village, Datong city, Shanxi Province, Northern Wei Dynasty. (Photograph by Gao Feng)

**Supplementary Files**

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- *Appendix.docx*