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The technique of red painting for bronze artefacts unearthed at Sanxingdui site, Sichuan, China

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A large number of painted bronze artifacts were unearthed from the sacrificial pits at Sanxingdui, reflecting the outstanding bronze decorative techniques of ancient China. The material of red pigment, binding agent and decorative painting techniques used on Sanxingdui bronze artifacts are revealed by this paper. Specifically, red-painted samples were collected from a bronze ware with a tiger head and dragon body. Analysis by Optical Microscopy (OM) and Scanning Electron Microscopy (SEM) showed that the painted decoration was created through a multi-layer coating process. Raman spectroscopy and SEM-EDS analysis confirmed that the material of red pigment is cinnabar. Analysis by Bicinchoninic Acid (BCA) and High-Performance Liquid Chromatography-Mass Spectrometry (LC-MS) confirmed that the binding agent was not animal glue. Furthermore, Infrared Spectroscopy (IR) and Gas Chromatography-Mass Spectrometry (GC-MS) analysis revealed that the red cinnabar pigment was bonded by lacquer. Based on the analytical data above, it can be inferred that the red in the grooves of sunken decors on Sanxingdui bronze wares was conducted by a multi-layer filling process. Firstly, lacquer was applied within the grooves, and then before it got fully solidified, a cinnabar layer was added for coloring. The cinnabar particles were gently pressed to secure them in the lacquer, with some particles embedding into the lacquer layer. The cinnabar and lacquer layers were applied alternately till the grooves were filled with red. The present study clarifies the filling process of red-painted decoration on Sanxingdui bronze wares, enhancing the understanding of the appearance of bronze civilization in ancient Shu as well as in Southern China.

The painted bronze generally referring to bronze wares with colored designs or ornaments applied to the surface. However, it can also refers to bronze wares decorated with pigments in a broader context. Bronze wares with sunken decor grooves filled with color pigments should also be regarded as the painted bronze ware thereby. Painted bronze artifacts, as a unique type of bronze ware, are not only masterpieces of ancient craftsmanship but also significant social and cultural heritage of ancient China. Religious beliefs, social customs, and cultural characteristics are contained by the special features of special artistic appearance of painted bronze wares, attracting substantial academic interest of archaeologists, art historians and technical historians. Moreover, dozens of painted bronze artifacts have been unearthed by the newly archaeological excavations at Sanxingdui in 2019, which become the focus of the world's attention.

In the Bronze Age of China, there were relatively few painted bronze wares. At present, it is generally believed that early Chinese painted bronzes are first discovered in the late Shang Dynasty and developed rapidly during the Eastern Zhou Dynasty[1]. But in fact, the appearance of painted bronze ware should be earlier. Su Rongyu points out that brown or gray fine substances can be seen filled in the grooves of casting patterns of bronze wares in the Erligang period, which are used to highlight the cast-in designs of the bronze ware[2].

The number of bronze wares with black or red filling patterns of the late Shang Dynasty and Western Zhou Dynasty is relatively larger. Among them, bronze vessels with black fillings have long been concerned. As early as the 1930s, Bishop William C. White notices that a bronze Ding (a kind of bronze vessel) unearthed in Luoyang is filled with black substances in its sunken décor[3]. Herlee G. Creel speaks of the black and calls it a pigment[4]. Bronze vessels of the British Museum were studied by Harold J. Plenderleith who notes:"The black powdery inlays in Shang bronzes have proved to be mostly residues of carbon with some silica and phosphorous. This seems to support the common belief that such black inlays in Shang bronzes may be remains of some primitive form of lacquer of organic origin."[5]. Further observation and analysis of Chinese bronze vessels in the Freer Gallery of Art made by Rutherford J. Gettens reveals the black fillings is quartz component which is quite similar in partical shape and size distribution[6]. It is not until the Warring States Period that the number of printed bronze wares gradually became considerable. A relatively a type of bronze mirror appeared, featuring decorative patterns and designs painted on the backside, commonly found in the regions of Chu, Qi, and Luoyang[7], a number of painted bronze carriages, horses, and waterfowls unearthed in the mausoleum of the First Emperor of Qin[8] reflect that at the end of the Bronze Age in China, painted bronze wares were relatively common.

The material of ancient paintings generally consists of two basic components: colorants and binding agents. Ground mineral, vegetal pigments as well as chemically synthesized pigments are used as colorants[9,10]. The pigment composition can be detected by polarized light microscopy[11], Raman spectroscopy[12], X-ray diffraction[13], X-ray Fluorescence[14] and SEM-EDS[15]. Through these scientific and technological archaeological methods, the composition of ancient pigments of various colors has been revealed in general: White pigments are usually lead white and gypsum[16], red pigments are mainly iron oxide or cinnabar, black pigments may be carbon black or manganese oxide[17], blue and green pigments may be copper-containing minerals such as malachite and natural or synthetic azurite[18].

Among the pigments mentioned above, cinnabar was an important pigment and funeral ritual item in ancient China from the Yangshao period to the Warring States period, and was widely used in tombs, human bones, and oracle-bones[19]. As early as the 1930s, Li Ji has already noticed the use of cinnabar in tombs and bones[20]. Further scientific analysis conducted on the red pigment used in oracle bone inscriptions confirms that its material is cinnabar[21]. It is worth noting that in nature, antimony (as well as arsenic, selenium, and tellurium) is commonly found in the primary ores of cinnabar, which is one of the main methods for distinguishing natural cinnabar from synthetic cinnabar[22].

Binding media or agent is the other significant component in painting. Materials such as lacquers, oils, glues, resins, and even beeswax were applied together with the pigments to help the pigments adhere to the surface of the object. The adhesion ability of color pigments on the surface of bronze wares is worse than that of porous materials such as pottery, making cementing materials particularly important. Methods such as BCA protein test, high-performance liquid chromatography-mass spectrometry (LCMS) and gas chromatography-mass spectrometry (GCMS) are commonly used to analysis the composition of cementing materials[23–25].

There are two main methods for bonding the pigment layer to the bronze base. One is to paint directly with pigments mixed with animal or vegetable glue without applying primer beforehand. The other is the lacquer painting method, in which there is a transition layer between the base and the pigment, making the two parts combined tightly. For example, for the bronze coloring process of the Qin Dynasty, a white layer consisting of natural resin and hydroxyapatite with silicon oxide filler was first applied to the surface of the bronze to form a transitional layer, then the pigment was used for painting[26,27].

The Sanxingdui Site, located in Guanghan City, Sichuan Province, is the most important regional center site in the pre-Qin period in Southwest China. a large number of bronze wares were unearthed from the Sanxingdui K1 and K2 sacrificial pits in 1986, including at least 40 painted bronze wares according to a previous statistical data[28]. In 2019, the excavation of the Sanxingdui Site was restarted, and more painted bronze wares were unearthed in the newly discovered six sacrificial pits K3-K8. According to the incomplete statistics by the author, painted bronze wares are mainly found in K3, K7, and K8, of which more than 70 pieces were unearthed in K3 alone. Among all the site known in the Chinese Bronze Age, the number of painted bronze wares of Sanxingdui Site is the largest and the artistic features are also the most diverse.

The excavation report said that the six sacrificial pits of K1-K4, K7 and K8 were roughly of the same age, which was the fifth phase of the Sanxingdui Site, equivalent to the fourth phase of the Ruins of Yin Xu[29]. According to the C-14 dating of Sanxingdui K4, there is a 68.3% probability that the burial time will fall within 3072-3003 cal. BP and a 95.4% probability that it will fall within 3148-2966 cal. BP[30], reflecting the production age of the painted bronze wares in Sanxingdui Site roughly as long as the time gap between the production and burial of bronze wares is not taken into account.

It is noteworthy that from the late Shang Dynasty, although the painting on bronze wares in the Central Plains developed rapidly, it was found almost only on bronze ritual vessels. The painted bronze wares unearthed at Sanxingdui Site also include human figures, divine beasts and other bronze statues in addition to vessels, showing the unique features of the ancient Shu civilization.

To address the issues of the materials and techniques of red painted bronze wares of Sanxingdui Site, this paper carries out a series of scientific and technological analyses of the materials and painting techniques of the Sanxingdui painted bronzes, which helps to reveal the diverse civilization of ancient Chinese Bronze Age.

Materials and Methods

Surface decoration bronzes. The number of painted bronze artifacts in Sanxingdui is quite considerable with over ten painted bronze wares unearthed from Pit 8. Figure 1 shows a typical bronze Lei vessel with almost the same shape of one from the southern region of China while the

Fig. 1 | Bronze Lei K3QW:14.

Fig. 2 | The photo of bronze Zun with a human head K3QW:828.

Fig. 3 | The photo of bronze standing portrait holding a dragon K89:66.

decorative grooves are filled with red pigments. However, some painted bronze wares excavated from Sanxingdui are quite different in shape with local characteristics of ancient Shu in Sichuan province in China, such as a series of bronze Zun vessels on the top of a human head shown in Figs. 2 and 3, etc. The main colors of painted objects are red and black. Red pigments applied to the sunken decors of the objects are also known as filling colors.

Samples. The sample in this study was small fragments with coloring on the surface of K89:520 with a tiger head and a dragon body excavated from Sanxingdui. The three representative samples come from different parts of the object, as shown in Fig. 4.

Methods

Stereo microscope observation. An optical stereo microscope (SX-6, Shanghai Optical Instrument No.1 Factory) with a digital camera (MC170 HD, LEICA) was used to observe and photograph the details of the samples.

Scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS). PHENOM XL scanning electron microscope with energy dispersive spectrometer under 15 kV of accelerating voltage, 3.5 kV of beam intensity. The probe mode of SEM was backscattering and of EDS was lines-map sweeping under high-vacuum conditions (1 Pa).

Microscopic laser Raman spectroscopy (LRS). The equipment was Renishaw inVia from UK using a 532 nm air-cooled DPSS (diode-pumped solid-state) laser with a maximum power of 50 mW. The samples were viewed under a Leica microscope at 50× telephoto with a grating of 1800 l/mm. The spectral resolution was 1–2 cm^{-1}. The laser power was 5% of the maximum and the exposure time was 10 s. The number of accumulation was 2–4. The spectral range was 100–3800 cm^{-1}. The data collection and analysis software was Renishaw WiRE 4.1.

Protein analysis. The presence of protein components in the colored adhesive material was analyzed and detected using Bicinonic acid (BCA)

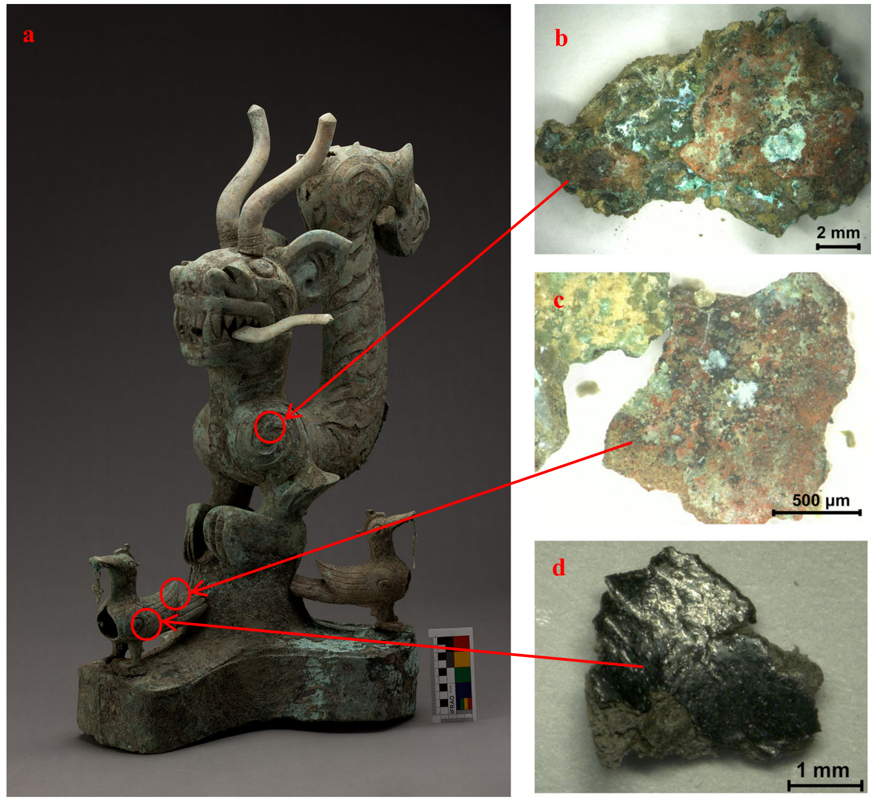

Fig. 4 | Painted sample collected from bronze ware K89:520 with a tiger head and a dragon body. **a** The photo of K89:520 with a tiger head and a dragon body. **b** Small sample pieces of K89:520-8, **c** Small sample pieces of K89:520-14. **d** Small sample pieces of K89:520-13.

protein concentration detection and liquid chromatography-mass spectrometry (LCMS).

BCA protein testing. For BCA protein analysis, the samples were extracted by ultrasonic oscillatory using 2% Triton X-100 after 1 week of immersion at room temperature. The protein can reduce divalent copper ions to cuprous ions. Under alkaline conditions, BCA was applied to form a purple complex with maximum absorption at 540-590 nm. Obtain the working curve through calibration by the BCA quantitative reagent kit.

High-performance Liquid chromatography-mass spectrometry (HPLCMS). The catechol structure in lacquer sap was analyzed using a Shimadzu high-performance liquid chromatography-mass spectrometry system (LC-30ADSF-LC-30AD-8050 MS, Shimadzu, Japan). HPLC Conditions: The chromatographic analysis was performed at a flow rate of 0.8 mL/min. The mobile phase consisted of methanol and a 10 mmol/L ammonium acetate aqueous solution. The column temperature was set to 35 °C, and the injection volume was 10 μL. Mass Spectrometry Conditions: Mass spectrometric analysis was carried out with a drying gas flow rate of 7.0 L/min, a drying gas temperature of 350 °C, and a scan range of 50–1200 m/z.

Fourier transform microscopy infrared spectroscopy (FTIR). Using the Spotlight200 micro infrared spectrometer from PE company of the United States. The testing conditions are: potassium bromide tablet, micro infrared wavenumber range: 4000–650 cm^{-1}, scanning frequency of 64, scanning step size of 2 cm^{-1}. The spectrum was analyzed by Omnic 9 software.

Gas chromatography-mass spectrometry (GCMS). Shimadzu QP2010/T8050 gas chromatography-mass spectrometry (GC-MS) was performed on a DB-5MS capillary column, 30 m × 0.25 mm, 0.25 μm. Chromatographic conditions were as follows: The initial temperature was 30 °C and held for 5 min. Then, it increased to 250 °C at a temperature rate of 20 °C/min and held for 5 min. The inlet port was the non-split mode and the temperature was 230 °C. The auxiliary heater temperature was 270 °C. The mass spectrometry was acquired in EI mode with a voltage of 70 eV and a recording range of m/z 33–700 amu. The TIC mode was used for the peak detection of the full ion-flow map and matched with the NIST 2017 spectral library.

Results and Discussion

Morphology of the painted sample. The painted surface and cross-section morphology were observed by a stereoscopic microscope. Figure 5 shows the shape of different areas on the sample surface of K89:520-14. The overall distribution of the red color painting in Fig. 2a was blocky and distinctly granular. It was surrounded by bluish-green patches of bronze patina and dirt. In addition, many black and lumpy solids coexisted with the red pigment or were distributed in filamentary connection. The shedding of the red pigment in Fig. 2(b) shows that the cementing agent on the bottom is a kind of black material in a greasy state with a small number of red pigment particles dispersed in it.

Figure 6 shows the cross-section of color painting observed under a stereoscopic microscope. It shows a layered peeling phenomenon, with black and red layers. The bronze ware has been buried for more than 3000 years and has been severely rusted. The painted layers have been damaged by rust products and are structural blurring in appearance, which makes it

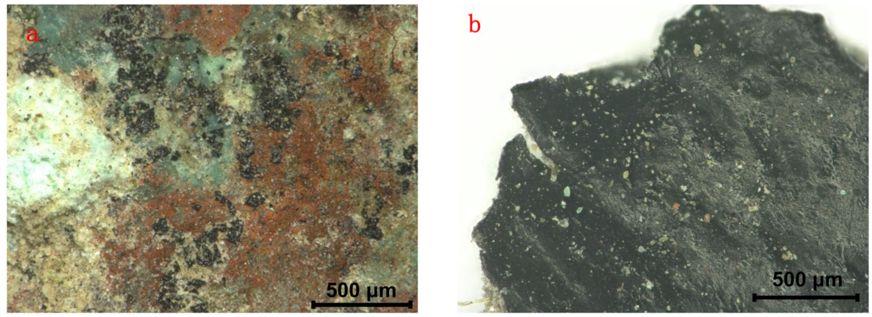

Fig. 5 | Surface morphology of colored samples of K89:520. a Surface morphology of sample K89:520-14. **b** The point where the red pigment fallen off from sample K89:520-13.

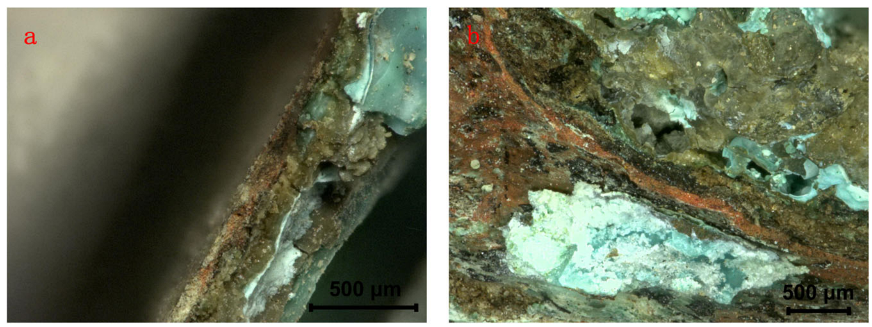

Fig. 6 | Cross-section morphology of colored samples. a Sample of K89:520-14; (**b**) sample of K89:520-8.

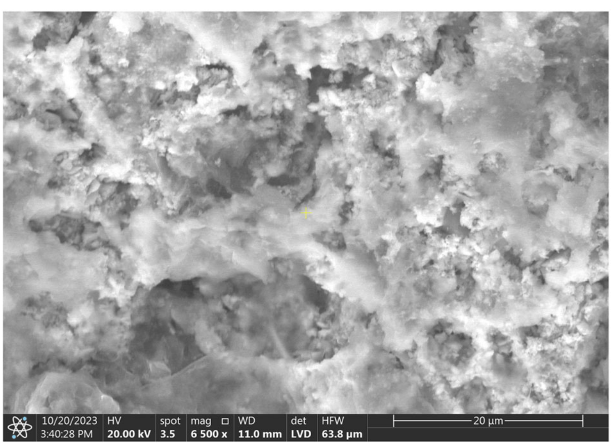

Fig. 7 | SEM morphology of red pigment.

difficult to reveal their relationship. Some painted surface even has been deeply contaminated by overlaying patina.

Composition of the red pigment. The analysis of the composition of Sanxingdui red painted pigments is the basis for revealing the painting techniques. SEM-EDS was used to analyze the surface morphology and chemical composition of painted samples, and the results are shown in Fig. 7. It can be seen that the red pigment is composed of aggregates of fine particles, with uneven surface pigment layers and traces of adhesive.

It is especially difficult to separate the small pigment particles and the binders. Therefore, a compositional surface scan was conducted on the entire area of the sample. The results are shown in Fig. 8, mainly reflecting elements such as Cu, C, O, Hg, Si, S, As, Al, etc. It can be inferred that Cu, C, and O elements mainly come from the corrosion products of the bronze ware, and C also shows the main composition of the cementing agent; Si and Al are mainly brought in by the interference of buried soil substances on the pigment layers. The distribution areas of Hg and S elements in Fig. 8d, f are highly overlapping. Table 1 shows the content of each component, with higher levels of Hg and S, indicating that Hg and S elements are the main components of the red pigment. Considering the common ancient red pigments, it can be inferred quite solidly that the red pigment of bronze wares of Sanxingdui is cinnabar(HgS). It is noteworthy that the content of S is relatively high, and there is also a certain amount of As in the areas where Hg and S are distributed. Besides, the distribution of As is quite consistent with the areas where S is distributed, indicating the possible existence of some realgar (As_4S_4) or orpiment (As_2S_3). They are all associated minerals of natural cinnabar, indicating that the red pigment used on Sanxingdui bronze wares should be natural cinnabar.

To verify the composition and structure of the red pigment further, micro laser Raman spectroscopy was used to analyze the surface and cross-section of the red pigment in the sample. As illustrated in Fig. 9, the Raman spectrum results of the surface test of the red pigment show that there are three representative characteristic peaks at Raman shifts of 257, 291, and 347 cm^{-1} in the Raman spectrum, which belong to the typical peaks of HgS[31], proving that the red painting pigment of Sanxingdui bronze wares is cinnabar again.

The composition and structure of different levels of tissue in the cross-section of the sample were detected by the laser Raman and the results are shown in Fig. 10. Spot selection testing was conducted for two layers of red pigment: the middle and the bottom layer. From Fig. 10, it can be seen that the Raman shift peaks of the two layers of red pigment correspond to the HgS characteristic peak. However, the middle layer of the red pigment is a

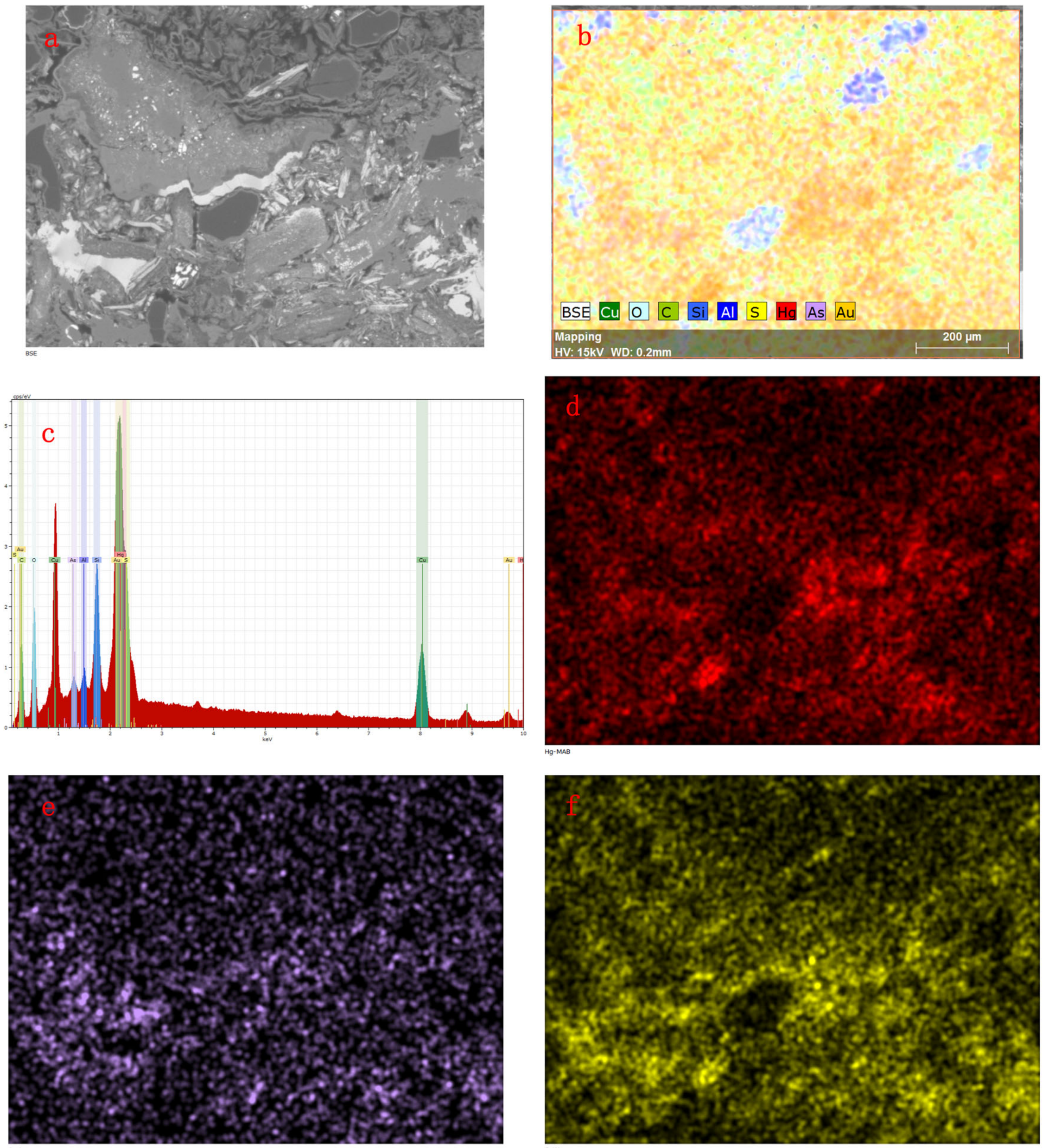

Fig. 8 | The results of SEM-EDS mapping mode of red painted area. (**a**) Electron microscopy morphology of red pigment. (**b**) Distribution of Elements (**c**) Element scanning results. (**d**–**f**) Hg, As and S element distribution.

Table 1 | The elemental content of red painted area by SEM-EDS mapping (Wt%)

Element	Cu	C	O	Hg	Si	S	As	Al
Content	41.57	17.37	14.82	13.15	5.08	4.78	2.18	1.04

kind of black substance, and it is mainly composed of amorphous carbon Raman shift peaks and weak cinnabar signals. The green substance at the bottom layer is detected to be a phase of malachite, which is a product of bronze corrosion. The Raman spectroscopy results of the cross-section sample are consistent with the SEM-EDS results, once again proving that the red pigment is cinnabar and indicating that there may be high carbon organic substances between the two layers of cinnabar. In addition, a certain amount of bronze corrosion products are mixed into the bottom layer.

Analysis of the cementing agent. It is already confirmed that cinnabar was used as the red pigment on the painted bronze artifacts from Sanxingdui by the laboratory analysis mentioned above. Given that cinnabar is a kind of granular solid which is difficult to adhere to the groove of decors independently, it is speculated that binding materials may have been used.

In ancient Chinese artifacts, binding materials include two major categories in common: the animal glue and plant-based adhesive. The

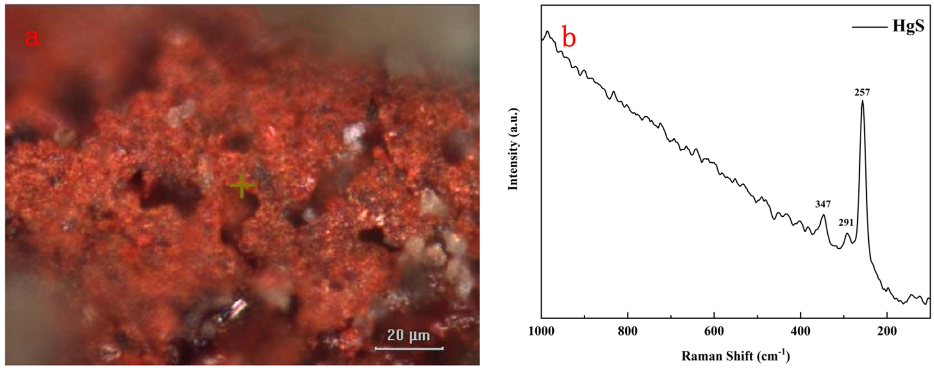

Fig. 9 | Raman results of red painted area. **a** Microscopic photograph of red pigment. **b** Raman spectroscopy of red pigment.

animal glue, derived from animal skins, bones, or tendons, contains protein components inherently. The plant-based adhesive such as rice glue and peach gum, includes various resins, crushed seed mixtures, and starches or dextrins extracted from grains. In terms of the composition, animal glue typically contains proteins, whereas plant-based adhesive, apart from lacquer, is composed of hydrocarbons without protein components. In addition, lacquer as an important and common ancient plant-based adhesive, contains aromatic benzene ring structures.

Therefore, in the experimental analysis, BCA and liquid chromatography were first employed to detect the presence of protein components in the binding material, with specific procedures described in detail in the Materials and Methods section. The BCA test is highly sensitive for detecting protein composition. However, no signal indicating the presence of protein was detected. In the liquid chromatography analysis, only a single chromatographic peak identified as the protein solution substance Triton X-100 was observed, which means no effective data of protein and peptides has been detected by LC-MS either. This result indicates that the binding agent for the red-painted decoration is not any kind of animal glue.

Since animal glue was not used as the adhesive for the red pigment, there is a higher possibility that lacquer or another plant-based adhesives was employed. Therefore, FTIR and GC-MS were selected to analyze the samples, with the results shown in Figs. 11 and 12.

For the black sample block in Fig. 4d, three small areas were selected. The results of micro infrared spectroscopy analysis are shown in Fig. 11. The infrared absorption peaks of the three curves in the figure show good consistency. According to the relevant literature[32], the corresponding functional groups for each absorption peak in the spectrum are: 3330 cm^{-1} is the absorption peak of carbonyl O-H, 2919 cm^{-1}, 2851 cm^{-1}, and 1465 cm^{-1} correspond to the absorption peaks of long carbon chains CH_2 and CH_3, 1728 cm^{-1} is the absorption peak of carbonyl C = O, 1598 cm^{-1}, and 1535 cm^{-1} are the characteristic absorption peaks of the benzene ring. In the fingerprint range, there are peaks indicating the phenolic benzene ring hydroxy C-O between 1300 and 1100 cm^{-1}.

From the results above, it can be preliminarily inferred that the sample contains the composition of lacquer, where the hydroxyl group and the benzene ring are carried by lacquer phenol.

In order to further verify whether the bonding material is lacquer, GCMS was used to analyze and test the black small blocks, and the results are shown in Fig. 12. The sample is cracked into multiple components, and there are a large number of cracked products with benzene ring groups in the data. In the chromatographic elution curve of Fig. 12, the peaks appearing at retention times of 7.825, 9.430, 10.540 and 10.825, are all substances with benzene ring structures.

Mass spectrometric analysis was performed on the chromatographic effluents, and the results are shown in Fig. 13. By comparing with the mass spectral library, the chromatographic peak with a retention time of 7.825 min was identified as 1,2-dimethylbenzene (o-xylene). The peak mass to charge ratio of 106 is the molecular ion mass of ortho xylene, and the peak mass to charge ratio of 91 is the fragment ion mass of the benzene ring after the removal of one methyl from ortho xylene. In addition, the chromatographic peaks with a retention time of 9.430, 10.535, and 10.825 are identified as 1-methyl-2-(1-methtylethyl) benzene, 1,2,4,5-tetramethyl benzene, and 1,3-bis(1-methtylethyl) benzene, respectively.

According to the relevant literature[33], these components consist of fragmented molecular structures with benzene rings may be produced by lacquer cracking. Among the common ancient plant-based adhesives, only the degradation products of lacquer contain substances with benzene ring structures.

Based on the GC-MS results, benzene ring components were detected in the composition of the painted binding material. Combining the results of infrared spectroscopy analysis and observations by the stereomicroscope, this material appears to be a black, oily, glossy substance that can be identified as cured lacquer with a high probability. Furthermore, several bronze human heads with gold masks were unearthed at the Sanxingdui Site. The gold mask and bronze head are bonded by a mixture of raw lacquer and clay, indicating that the ancestors of Sanxingdui were skilled in using lacquer as a bonding material[34]. Considering all these results and factors, it can be inferred that natural lacquer was used as the binding material for the red painting on bronze artifacts of Sanxingdui site.

Painting technique. Based on the analysis of the red-painted area, it can be determined that cinnabar(HgS) was selected as the raw material for the red pigment. In order to fix the cinnabar particles on the surface of bronze wares, lacquer was used as the bonding or cementing material.

How did the red be painted onto the bronze wares in Sanxingdui Site is the next issue to be addressed. In the following study, the photomicrographs of the sample provide key clues for exploring the color application process. Most of the red pigment was in the grooves of the bronze wares. As it can be seen in Fig. 14, the cross-section contains multiple colored layers. From the bottom to the surface, totally five colored layers can be clearly distinguished. The five layers are divided into three layers of black and two layers of red, which are arranged alternately in color. It is noteworthy that the outermost layer of black is relatively thin and discontinuous. According to the laboratory analysis and observation conducted by this paper, the red layers are mainly composed by cinnabar and the black layers are proved to be composed by lacquer as the binding agent. In another word, the red-colored

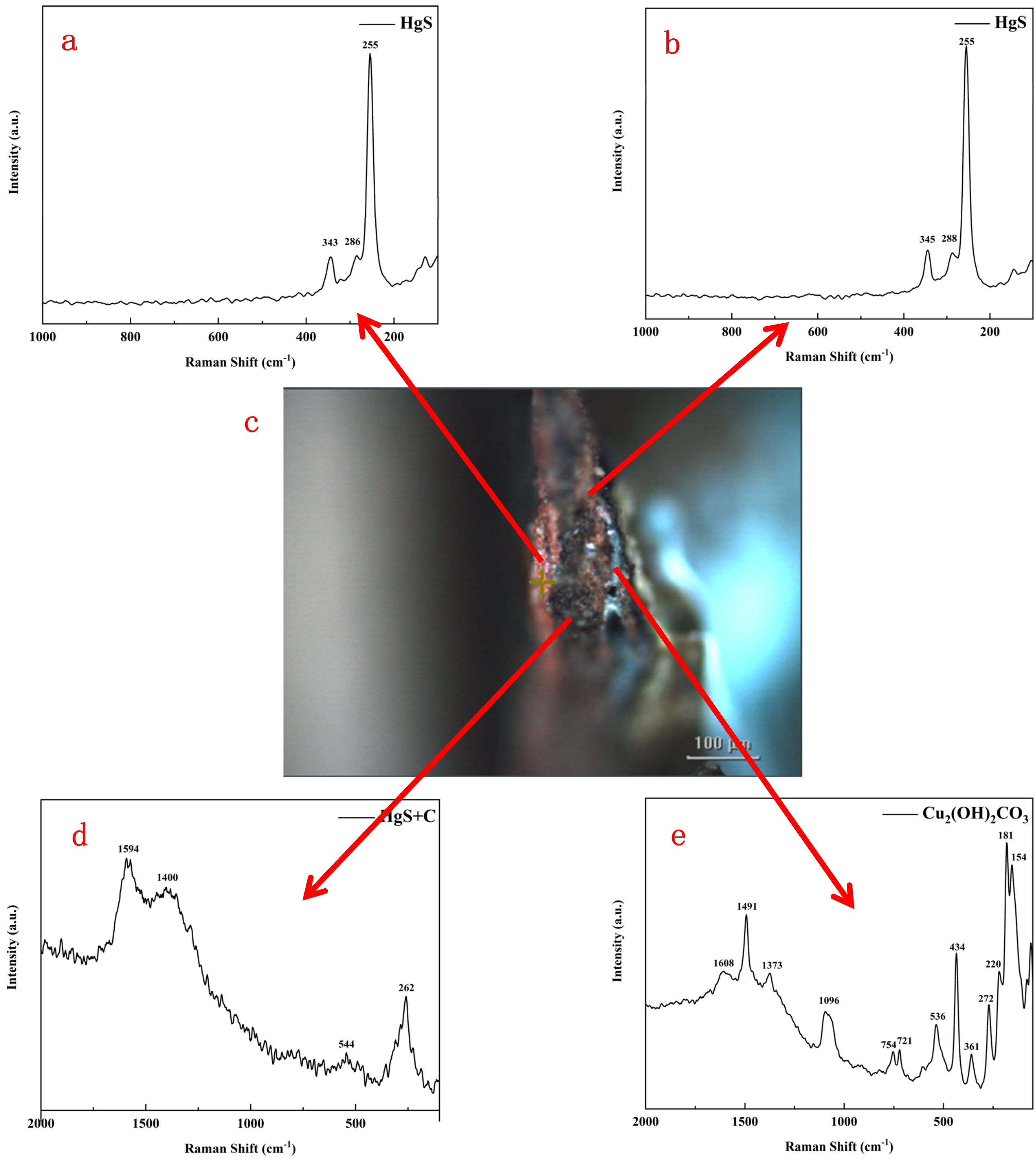

Fig. 10 | Raman results of different layers of sample cross-section. (**a**) Outer red pigment, (**b**) Inner red pigment, (**c**) Cross-sectional morphology. (**d**) Black substance in the middle layer, (**e**) Green rust in the bottom layer.

cinnabar layers are fixed by layers of black lacquer, filling in sunken decors of bronze wares of Sanxingdui Site.

The black cementing layers and red painting layers are obviously applied layer-by-layer independently rather than mixed together and the layers are quite thin with an average thickness of 40–60 microns. Considering the influence of corrosion products, the layers should be flat when the painting was applied in the early age. Figure 15 shows a thin and separated layer of black cementing material formed by lacquer with bronze patina mixed in it. Furthermore, Fig. 16 shows that some red cinnabar particles can be distinguished to be diffused in the lacquer layer, which can

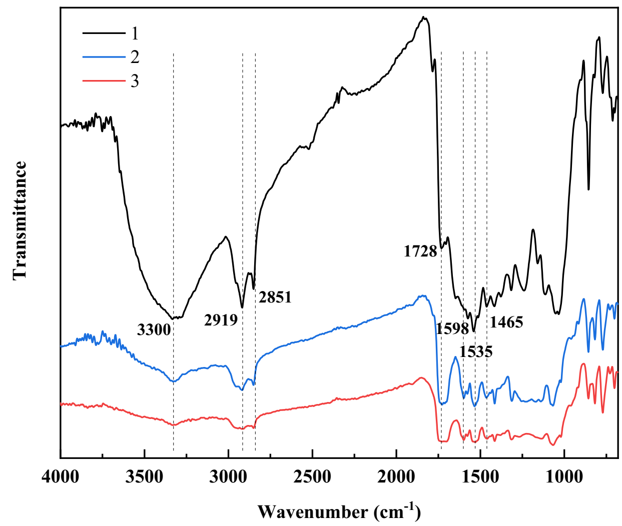

Fig. 11 | Microscopic infrared spectroscopy test results.

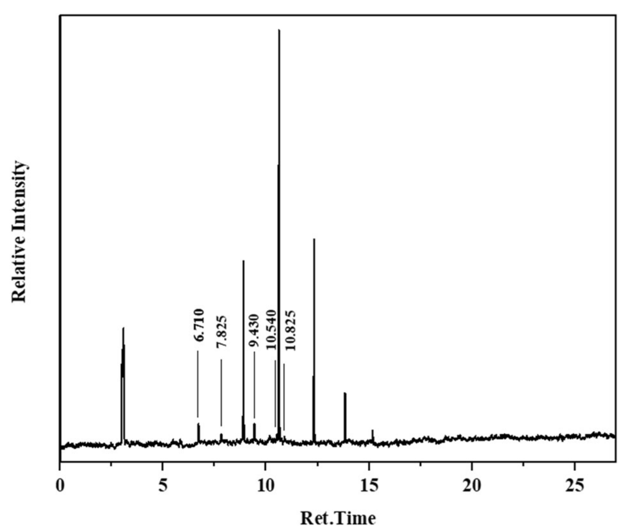

Fig. 12 | The outflow curve of gas chromatography.

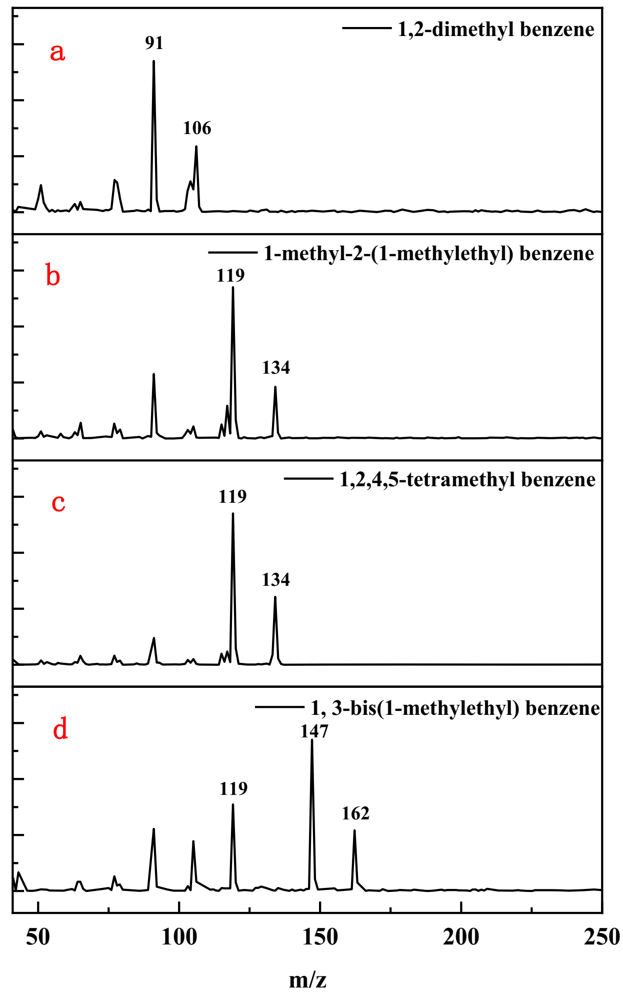

Fig. 13 | Mass Spectra of Chromatographic Effluents at Different Retention Times. (**a**) 7.825, (**b**) 9.430, (**c**) 10.535, (**d**) 10.825.

be caused only by squeezing. It can be inferred that after applying the cinnabar layers, a certain kind of squeezing process was conducted and some cinnabar particles were mixed into the lacquer layers.

The process of painting can be deduced as follows: A lacquer layer was applied first. Before the lacquer layer got solidified, a cinnabar layer was applied on it and was pressed at a delicate degree to adhere tightly onto the lacquer layer. This procedure was conducted at least twice to fill the grooves, forming the four layers can be observed on cross-section photomicrographs. The fifth layer in Fig. 14 may suggests that more layers of cinnabar as well as lacquer were applied at that time.

Conclusion. In a considerable number of bronze artifacts excavated at Sanxingdui Sacrifice Pits, it is noted that red substance fills neatly and precisely the sunken decor, which achieves the function of highlighting the decorative patterns of bronze wares and enriching the artistic expression. By a series analysis mentioned in this paper, the red fillings are identified to

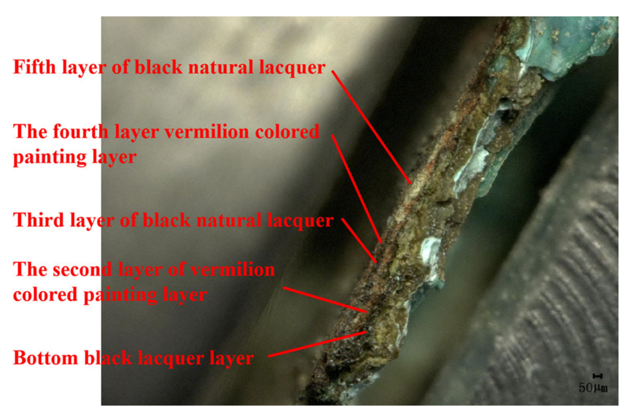

Fig. 14 | The cross-section of the colored sample.

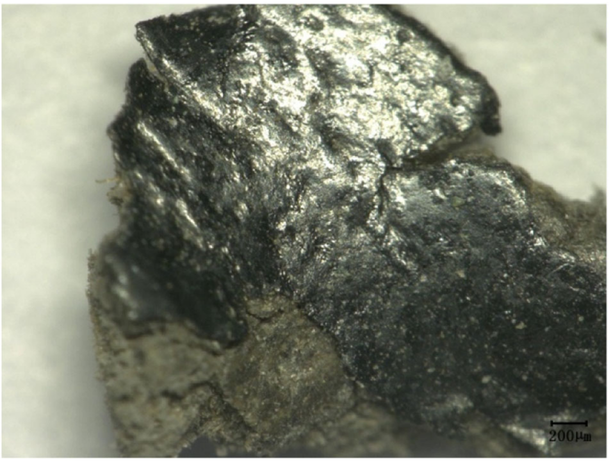

Fig. 15 | Surface morphology Of the lacquer layer.

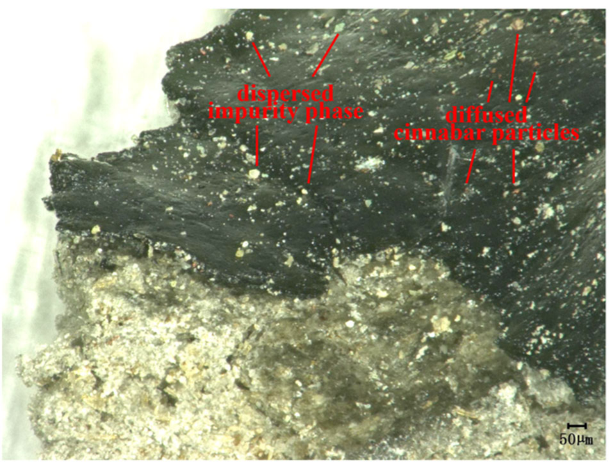

Fig. 16 | Dispersed pigment particles in lacquer.

be composed of natural cinnabar as the pigment material and raw lacquer as the cementing agent. The technique was further detected that a layer of lacquer was filled at the bottom of grooves and was overlaid with a layer of cinnabar then. The cinnabar layer was pressed at a delicate degree to adhere tightly onto the lacquer layer. This procedure was conducted twice or more so that the decor grooves could be filled fully and solidly by painting components.

In this case, the technique of the ancient lacquer ware was applied on the bronze ware, which reflects the unique technical and cultural feature of Sanxingdui. At present, studies and technical analysis of painted bronze wares are relatively rare, more observations and analysis are needed to reveal the origin and development of painted bronze wares in the Bronze Age in China.

Data Availability

All data generated or analysed during this study are included in this published article.

Abbreviations

SEM-EDS Scanning Electron Microscopy coupled with Energy-Dispersive X-ray Spectroscopy
LRS Micro Laser Raman Spectroscopy
LCMS Liquid chromatography-mass spectrometry
FTIR Fourier transform microscopy infrared spectroscopy
GCMS Gas chromatography-mass spectrometry

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Competing interests
The authors declare no competing interests.

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