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Characterizing ancient jade by on-site analysis in Sanxingdui, China

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Abstract

Characterized by various materials, types and patterns, ancient jade is a unique symbol of Chinese civilization. However, crucial information can be jeopardized by the sudden exposure during excavations, and abundant jade artefacts were stored without scientific identification in the archaeological context. Sanxingdui site was an essential center of a complex society in the Chengdu Plain in Bronze Age China. During the new excavation in Sanxingdui sacrificial area (pit K3–K8) since 2019, cabins have been used for better site conservation, providing ideal conditions for on-site study. Employing portable devices, on-site non-destructive analysis were conducted inside pit K8. The results of Raman and XRF show that the raw material is nephrite, indicating the consistency of jade material preference with the majority of Sanxingdui jade from pit K1–K2 and the majority of prehistoric jade as well. Evidence of mineral thermal phase transition from tremolite to diopside was found on the *zao* chisel and proved the existence of jade burning related to the sacrificial activities. The Fe content in the surrounding soil led to the red and orange colors on the jade surfaces and the neutral environment helped retaining of the original texture and natural luster of the nephrite. Based on the geometric morphometric database, the jade *zhang* forked blade was quantitatively recognized as the most typical *zhang* type only found in Sanxingdui. It is demonstrated that the non-destructive analysis is efficient to characterize the ancient jade and makes it possible to construct the database of all the jade artefacts on site, providing the basis of solving larger-scale archaeological problems that are not necessarily bounded by geographical regions or time periods.

Keywords Sanxingdui, Jade, On-site, Raman, XRF, Geometric morphometrics

Introduction

Due to the rarity and beauty, jade was usually opted to make prestige items for the elite, such as *zhang* forked blade, *zao* chisel, *ge* blade, collared *bi* disk and *cong* tube [1, 2]. The first known discovery of the Sanxingdui site that attracted academic attention was jade artefacts in the locale of Yueliangwan ('Moon Bend') on the south bank of the Yazi River in the Chengdu Plain of Sichuan in 1929 [3]. In 1986, the two famous large pits K1 and pit K2 (Fig. 1) containing a great amount of bronze, jade, gold objects, and elephant tusks were unexpectedly revealed, indicating that the Sanxingdui site was an important center of a previously unknown complex society [4, 5]. Among these hundreds of jade artefacts, one interesting phenomenon is that half of them show black and white colors on the surfaces with rough texture and low transparency, raising a speculation of burning sacrifice [3, 6]. Besides, the nearby Longxi nephrite [7] (Fig. 1B) was recorded in the ancient document of the *Han Book: Geographica* 汉书·地理志 as the important jade material in the Chengdu Plain, therefore the Sanxingdui jade artefacts were believed to be made of local jade materials

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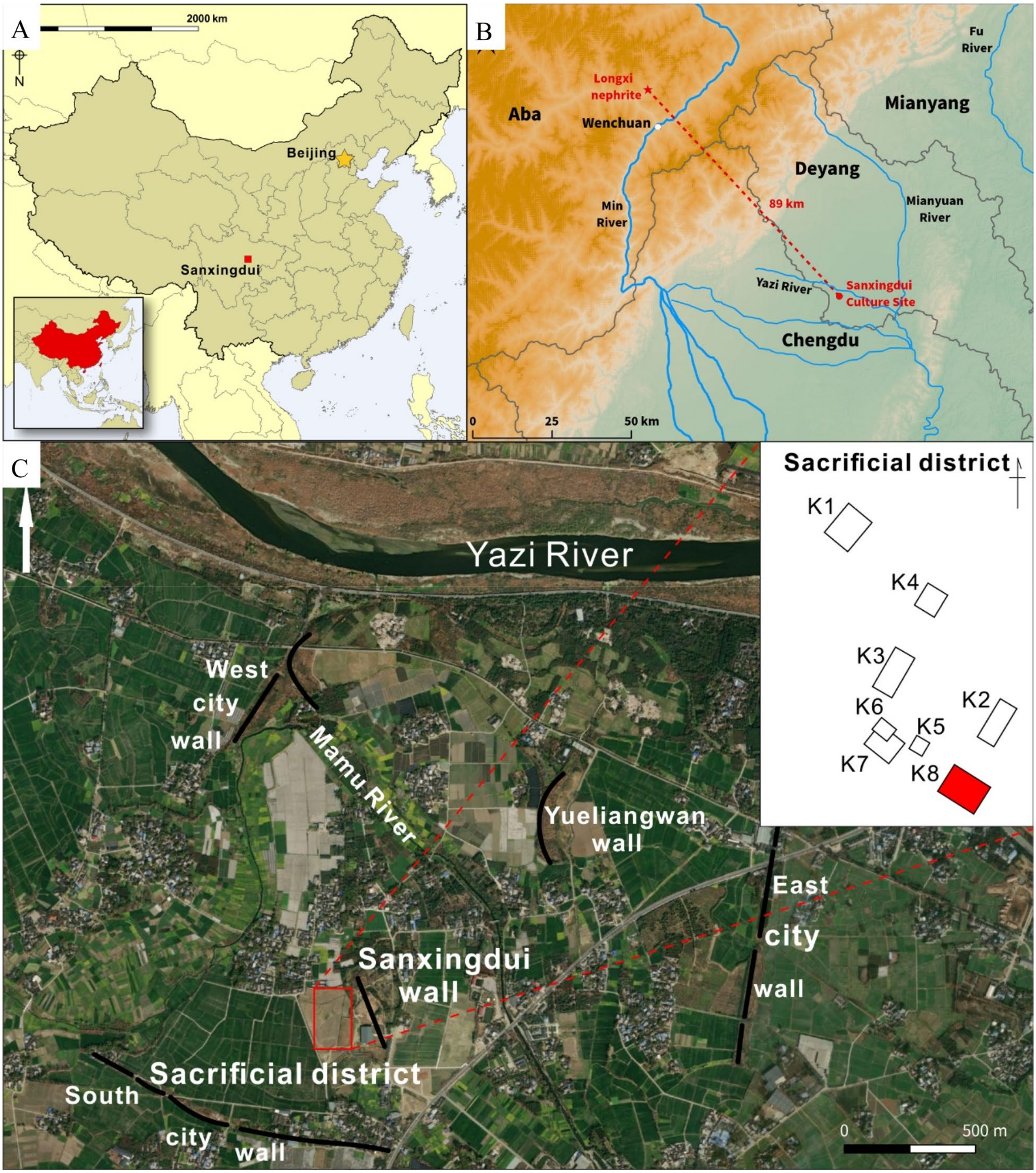

Fig. 1 Location of Sanxingdui (**A**), Longxi nephrite (**B**) and the pits K1–K8 (**C**) (Wall areas were identified by excavation and probing)

different from those of Central Plains Region [5, 8]. These archaeological findings and speculations keep in line with the evidences of the bronzes [9-11], further gemological and geochemical verification is required. Unfortunately, due to the lack of proper devices and systematic concept of archaeological excavation at that time, most of the jade artefacts were collected and stored in museums without comprehensive identification of the jade materials, the burial environments and the typological characteristics.

Fig. 2 On-site non-destructive analysis and soil sample collection at pit K8 (**A** the archaeological context of the four jade artefacts and the operating condition for on-site testing; **B** Soil sampling around *zhang* forked blade; **C** Soil sampling around *guan* tubular bead; **D** Raman analysis of *zao* chisel)

It remains difficult to interpret the cultural connotation of these ancient jade given the short of comparable data.

Different from the excavation 33 years ago, six additional pits (K3–K8, Fig. 1), dating to Late Shang Dynasty and Early West Zhou Dynasty (ca.1200–1000 BC) [12], have been excavated inside a huge greenhouse-like shelter and integrated excavation cabins since October 2019 [13]. It provides a good chance to analyze the ancient artefacts and their surrounding soil in the archaeological context to reveal more information of the key archaeological issues in ancient jade research. Employing spectroscopy, geochemistry, and geometric morphology, this paper presents an on-site non-destructive analysis of jade material, burial environment and morphological characterization of typical jade artefacts from pit K8 of the Sanxingdui site.

Methods

Sampling

Four representative intact jade artefacts were selected and analyzed in the field when they were newly uncovered (Fig. 2; Table 1), including a *zhang* forked blade (Fig. 3A), a *guan* tubular bead (Fig. 3B), a collared *huan* ring (Fig. 3C) and a *zao* chisel (Fig. 3D). They were located in different cultural layers in potentially varied burial environments. Among them, the *zhang* forked blade and *zao* chisel were the types in the highest abundance in pit K1 and K2 discovered in 1986.

Table 1 Basic information of the four jade artefacts

Sample	Context code	Location	Jade color (original)	Alteration color	Transparency	Luster
Zhang forked blade	K8⑥YQ: 8	Layer No. 6	Green	Red and white	Opaque	Earthy
Guan tubular bead	K8⑦YQ: 4	Layer No. 7	Green-Gray	Orange	Semitransparent	Greasy
Collared *huan* ring	K8⑦YQ:44	Layer No. 7	Green	Orange	Semitransparent	Waxy
Zao chisel	K8⑦YQ:40	Layer No. 7	Green	White	Opaque	Waxy

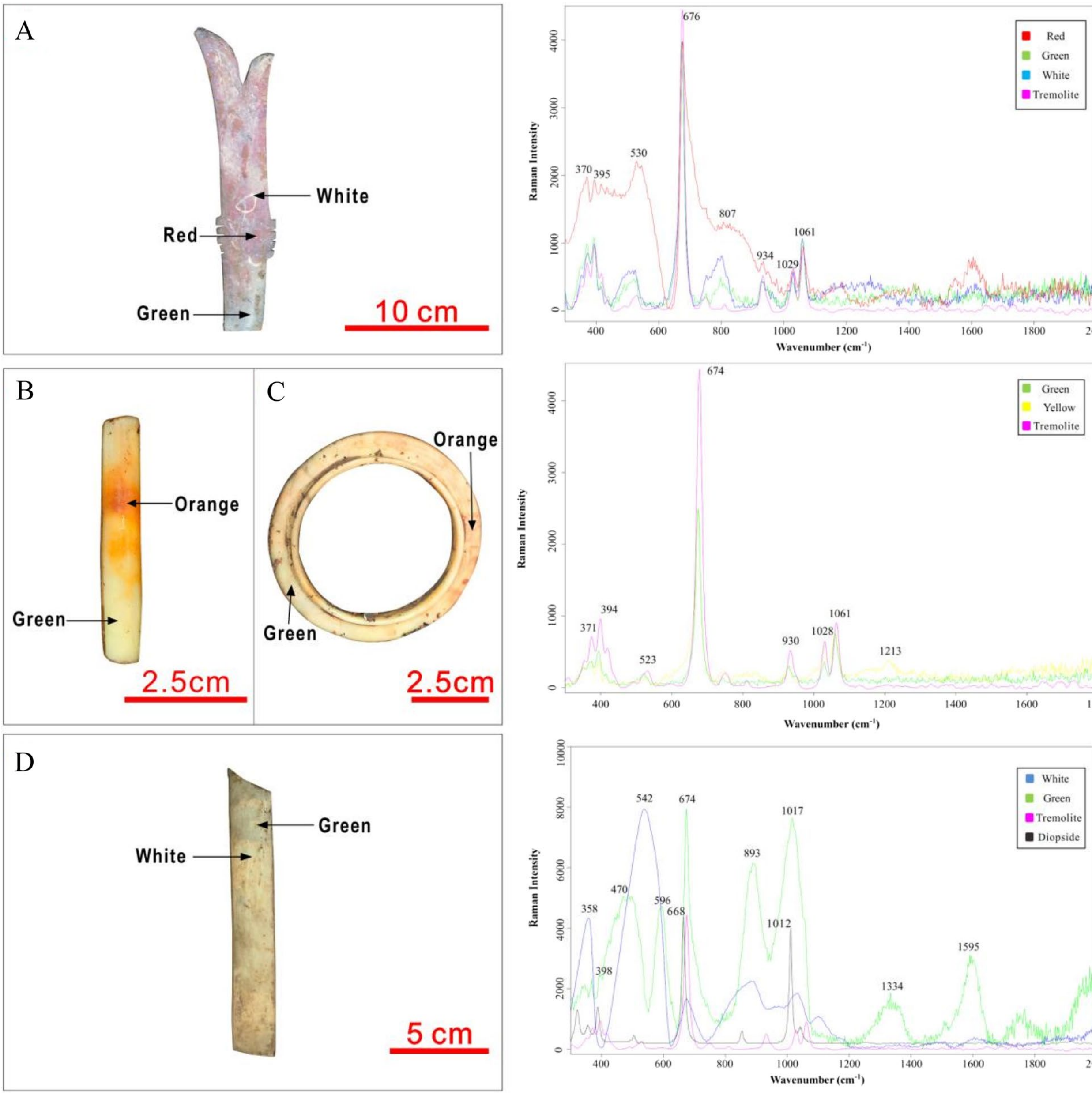

Fig. 3 Photographs and Raman spectra of the four jade artefacts from Sanxingdui pit K8 (**A** jade *zhang* forked blade, K8⑥YQ: 8; **B** jade *guan* tubular bead, K8⑦YQ: 4; **C** jade collared *huan* ring, K8⑦YQ:44; **D** jade *zao* chisel, K8⑦YQ:44; Standard Raman spectra of tremolite and diopside from the Database of The RRUFF™ Projec. https://rruff.info/)

The four jade artefacts from Sanxingdui pit K8 are in light colors with medium glossiness, and the *guan* tubular bead and collared *huan* ring have higher transparency. Only a few short and discrete cracks are on the surface of the *zhang* forked blade and *zao* chisel. Compared to the same types of jades from pit K1 and K2 with dark hues, chicken-bone white and low transparency visually, jade artefacts in pit K8 have finer texture and were less weathered. Soil samples were collected around these four artefacts by bamboo sticks (Fig. 2B, C) for pH test.

On-site Raman, XRF and pH analysis

For the jade artefacts, a portable Raman spectrometer (Bruker BRAVO) and a portable X-ray fluorescence spectrometer (Bruker TRACER 5) were applied for on-site non-destructive analysis. Based on patented fluorescence mitigation (SSE, Sequentially

Shifted Excitation) and dual laser (785 and 852 nm), the BRAVO automatically reduces the fluorescing by soil humus and enables the measurement of materials including dark and weak scattering samples. The spectral range is 3200 cm^{-1}–300 cm^{-1}. Raman results were processed by the software OPUS 5.5. The XRF (TRACER 5i) provides a measurement range of up to 48 elements with a 83-mm collimator and internal sample camera. The sampling time for each XRF spot is 60 s. And the XRF results were processed by the software Artax.

For the soil surrounding the jade, the pH of the soil samples was detected by a FiveEasy Plus pH meter (Mettler Toledo) and the elemental components were analyzed by portable XRF directly on the flattened layer around the jade in soil mode. The excavation was carried out under constant temperature and humidity. Thus, it is regarded that the exposure during excavation did not change the preservation of the jade artefacts. The chemical components and alteration are not affected by exposure.

On-site geometric morphometric analysis

In order to record more details of the jade artefacts in situ, it's a better choice to quantitatively extract and compare the morphological information of them. Considering the ritual significance and the typological diversity, the *zhang* forked blade was chosen for quantitative morphological analysis. Based on the traditional typological categorization, some *zhang* forked blades were not effectively distinguished from *ge* blades. Thus, the data of the *ge* blades from K1 and K2 were also included. The types conform to the excavation report [3]. For geometric morphometrics analysis, the selection of orientations and landmarks of the *zhang* forked blade is based on the posture in a bronze *zhang* forked blade held by the bronze figure unearthed from K2 (Additional file 1: Fig. S1), which was considered to illustrate the function of *zhang* forked blade during the rituals [14]. The photo was imported into the software *tpsDig2* with the back side on the left and the front side on the right [15]. A total of 21 landmark points that outline the shape of *zhang* and 106 sets of data (see Additional file 1) were imported into the software package geomorphic in RStudio [16] for principal component analysis (PCA). For further study of this type of artefact, 34 representative and well-preserved samples of *zhang* forked blades unearthed from other sites from Late Neolithic to Late Bronze Age were selected and divided into five areas: Yanshi-Shangluo, Shimao Shaanxi, Simatai Shandong, Southeast coastal area and Vietnam (see Additional file 1).

Results

Jade material

The identification of jade material is the basis of characterizing ancient jade artefacts. The mineral components by the Raman analysis and the elemental components by the XRF analysis distinguish jade materials noninvasively [17, 18]. The Raman spectra of the *zhang* forked blade (Fig. 3A) in different areas all have strongest peak at 676 cm^{-1} and medium strong peaks at 1061 cm^{-1}, 1029 cm^{-1}, 934 cm^{-1}, 807 cm^{-1}, 395 cm^{-1} and 370 cm^{-1}. Among these, the strongest peak at 676 cm^{-1} reflects the symmetric stretching vibration of $[SiO_4]$ (Si–O–Si); peaks at 1061 cm^{-1}, 1029 cm^{-1} reflect the anti-symmetric stretching vibration of $[SiO_4]$ (Si–O–Si); peak at 934 cm^{-1} reflects the symmetric stretching vibration of $[SiO_4]$ (O–Si–O); peaks at 530 cm^{-1} shows the vibration of $[SiO_4]$; peaks at 395 cm^{-1} and 370 cm^{-1} shows M–O (M = Ca, Mg, Fe) vibration [19, 20]. Thus, all the 3 spectra make it plain that the mineral component of the *zhang* forked blade is tremolite or actinolite and the color alteration did not change the mineral structures. What's worth noticing, the tremolite or actinolite could be distinguished by Raman peak numbers at 3600–3700 cm^{-1}, which is out of the range of portable Raman. The Mg/(Mg + Fe) value, R^*, is an effective way to distinguish the two minerals with the same chemical formula of $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$ [18, 19]. Given that the Fe substitution for Mg in actinolite is more than that in tremolite, the R^* of tremolite is higher than 0.9. In this case, it can be determined that the jade material of the *zhang* forked blade is low-Fe nephrite (Table 2) mainly consisted of tremolite.

Similarly, the *guan* tubular bead and collared *huan* ring (Fig. 3B, C) were also made of nephrite with no mineral components or crystal structure alterations in the orange areas. On-site XRF results indicate that the FeO_X, Al_2O_3, MnO, and CuO have obvious content variations in the red and orange areas, related to the post-burial weathering [21]. The Raman peaks of the *zao* chisel (Fig. 3D) at 674 cm^{-1}, 398 cm^{-1} and 368 cm^{-1} indicate spectra of nephrite in the green area, and the peaks around 1595 cm^{-1} and 1334 cm^{-1} reflect fluorescence interference. The *zao* chisel (Fig. 3D) has more information in the Raman spectra. The disappearance of peaks at 1061 cm^{-1}, 1028 cm^{-1}, 930 cm^{-1}, and 532 cm^{-1}, the show-up of peaks at 1017 cm^{-1}, 893 cm^{-1} and 596 cm^{-1} for the green area, and the show-up of peaks at 542 cm^{-1} and 358 cm^{-1} for the white area hint a thermal phase transformation from tremolite to diopside [22-24]. This provides the proof of jade burning. However, the motivation of jade burning needs to be further studied.

All the four jade artefacts in Sanxingdui pit K8 were made of low-Fe nephrite with original jade color of green,

Table 2 Chemical composition analysis of the four jade artefacts(wt%)

Sample	SiO_2	MgO	CaO	FeO_x	Al2O3	MnO	CuO	P_2O_5	K_2O	TiO_2	Total
Zhang											
Green	63.17	23.56	10.86	0.53	1.12	0.00	0.24	0.11	0.30	0.00	99.89
Red	61.24	21.61	10.60	1.31	4.63	0.14	0.02	0.10	0.28	0.04	99.97
White	61.62	22.78	11.27	1.19	2.67	0.15	0.03	0.08	0.15	0.00	99.94
Guan											
Green	62.01	24.75	10.66	0.45	1.62	0.00	0.11	0.10	0.24	0.00	99.95
Orange	62.99	22.22	10.28	1.34	2.19	0.00	0.27	0.13	0.39	0.03	99.85
Huan											
Green	63.83	22.27	11.45	0.63	0.93	0.00	0.34	0.15	0.32	0.00	99.93
Orange	64.54	20.02	13.05	0.99	0.35	0.00	0.50	0.14	0.36	0.00	99.96
Zao											
Green	62.51	23.49	10.45	0.89	1.93	0.00	0.18	0.11	0.32	0.02	99.90
White	61.36	20.70	11.04	1.26	4.82	0.17	0.17	0.14	0.27	0.04	99.97

consistent with those from pit K1 and K2 [25]. The difference is that the jade artefacts from pit K8 remained the fine texture and natural luster of nephrite, no significant black hues or chicken-bone white were observed as in pit K1 and K2. To understand whether this difference resulted from the impact of soil pH or human activities, more data on burial environments in different pits are needed.

Burial environment

Although the weathering did not alter the mineral phase of the jade *zhang* forked blade, *guan* tubular bead, and collared *huan* ring from the above Raman results, the surface colors altered during thousands of years of burial. The color alteration during weathering is called '*qin*' 沁, which is an important character for identifying ancient jade. The burial environment affects the weathering degree of the ancient jade through the pH and the element migration. The large-scale studies on the pH of the soil in China show that the burial environment is acidic in the south and alkaline in the north in general [19, 26]. It results in the more prominent phenomenon of jade whitening in southern China. However, the pH value of the yellow soil buried in the *zhang* forked blade is 7.71 in the cultural layer No.6 and the pH values of the black soil around the *guan* tubular bead, collared *huan* ring, and *zao* chisel are 7.34, 7.18, and 7.49 respectively. It is evident that these jade artefacts were buried in nonacid soil ($pH > 5.5$ as in [26]) and consistent with the modern soil pH in Chengdu Plain ($pH = 5.8–7.5$ as in [27, 28]). This may be one of the reasons that the jade artefacts in pit K8 remained with fine texture and natural luster. Furthermore, the main cause of whitening on the *zao* chisel was mineral phase transition before burial rather than dissolution during burial. Given that none on-site soil data of pit K1 and K2 were reported, it is not able to compare the pH values of pit K1–K2 with pit K8 for chemical weathering influence evaluation. This emphasizes the significance of on-site analysis examined in the archaeological context.

The XRF spectra of soil on the different cultural layers show the yellow soil around the *zhang* forked blade from layer No.6 has much higher content of Fe and much lower contents of Ca, Mn, Cu (Fig. 4) than those of the black soil on layer No.7. The mechanism of red alteration on ancient jade hasn't been systematically studied [29]. According to soil process geochemistry, when the pH value is higher than 4.5, the iron ion is mainly in the form of $Fe(OH)^{2+}$ or $Fe(OH)_3$ [30] showing the color of red or reddish brown. In this case, the Fe^{3+} in the soil is the main cause of red color on the ancient jade, such as the nephrite *huan* ring (M89:11) from the Liangzhu site and the handle-shape jade artefact (99ALN M988:62) from the the Yinxu site [19]. The significantly higher content of Fe in the red area of the *zhang* forked blade in pit K8 (Table 2) indicate the widely distributed red color is related to the infiltration of Fe^{3+} from the relatively Fe-rich soil on layer No.6.

Although the content of Fe in soil on layer No.7 was not as much as layer No.6 (Fig. 4), the higher contents of Fe in the orange areas than in the green areas on both the *guan* tubular bead and collared *huan* ring also indicate the Fe-related orange alteration (Figs. 3B, C and 4; Table 2). For these two jade artefacts, the content of Cu is higher in the orange areas as well. The Cu-related yellow and orange alteration was reported in the nephrite artefact (1976AXT M5:364) from the Yinxu site [19]. However, the Cu in soil originates from the buried bronzes and the weathering of copper bearing minerals, and is affected by the pH of soil solution.

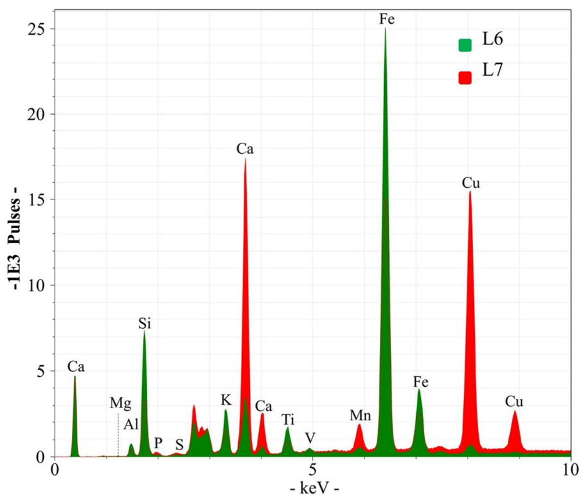

Fig. 4 XRF spectra of the yellow soil sample from layer No. 6 (L6) and black soil from layer No.7 (L7)

In neutral soil, the solubility of negative and cationic states of Cu decrease, and the $CuCO_3$ and $Cu(OH)_2$ are the main components [30], which are both green and blue. Whether the orange alteration was related to the Cu in the soil still needs further study in lab.

Typology

The geometric morphometrics analysis visualized the classification of the *zhang* forked blades. The shaded and lined areas represent the morphospace of a type, and the points within it means those samples have similar shapes. The colored shades are comprised of *zhang* forked blades and *ge* blades from Sanxingdui pit K1 and K2, and the colored lines are made up by *zhang* forked blades from other sites. The geometric morphometric data of the *zhang* forked blade from pit K8 (the marked yellow star of Fig. 5) fell into the overlap area of Sanxingdui Type 2 C (red shade), which means it can be classified as this type. It's completely distinguished from *zhang* forked blades from other relatively contemporaneous sites (lined boxes) and the *ge* blade from Sanxingdui K1 and K2 (yellow shading), which further supported the judgment above. It is noted that the morphospace of the Sanxingdui Type 1D almost completely overlies the morpho space of Type 1B (green shade), and partly overlaps with the morpho spaces of *ge* blade and Type 2 C. It is

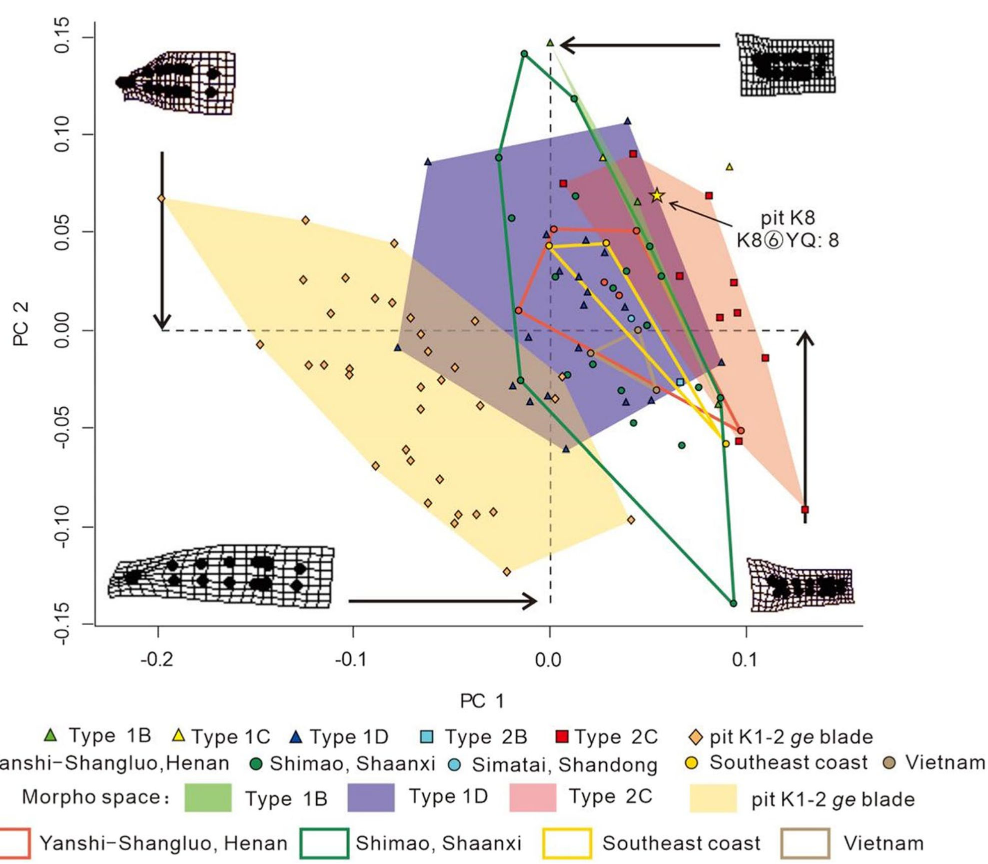

Fig. 5 The principal component analysis of jade *zhang* forked blades and *ge* blades

most likely that this type shares a lot of commons with other types, but still unique as it also has a potential of *ge*-blade-origin. The morphospace of Type 1B is slim and over lapped with that of Type 1D and Type 2 C, suggest a possibility that this type is hard to classify as an isolated type. Nevertheless, there are only three samples of Type 1B and one is outside any of the morpho spaces, so it is not clear whether Type 1B is an effective classification. Part of the morphospace of Type 2 C overlaps with other morphospaces, but most of it is aparted from them, indicating that this type is relatively effective. This type is thought to be the typical type of *zhang* forked blade, and this is supported by the PCA plot. The *zhang* forked blade from Shimao, Shaanxi, also occupies a slender morpho space, and completely includes the morphospace of the *zhang* forked blades from Simatai, Shandong, Southeast coast and Vietnam, and nearly all samples from Yanshi-Shangluo, Henan. That suggests the *zhang* forked blades from these areas are highly alike, indicates a closer relationship between them compared to Sanxingdui. Quantitatively speaking, these overlaps reflect that the qualitative morphological types have low quantitative distinction.

Discussion

Jade material preference

The jade material of these jade artefacts from pit K8 is low-Fe green nephrite, consistent with the majority of jade artefacts from K1 and K2 [25]. It further supported the view that the Sanxingdui people preferred green nephrite for ritual artefacts rather than white quartzite or marble, although the latter are more common in nearby. In fact, nephrite is widely distributed in China with a use history of almost 10,000 years [31], the preference for nephrite widely existed in China since the Neolithic [32-36]. In the Bronze Age, the nephrite artefacts played key roles in elite life [37, 38]. As mentioned in the first-to-second-century AD notes on rituals, '*cang bi li tian*苍璧礼天' in *Rites of Zhou* 周礼, the deep green jade was often taken as a communication medium for the elites to communicate with gods or ancestors [39].It is worth noting that in Chinese, in the *Shuo Wen Jie Zi* 说文解字 (famous literary work written by Xu Shen in the Eastern Han Dynasty), '*cang*' means 'grass color'苍,草色也, rather than blue. This might explain the extensive usage of green jades in the Sanxingdui sacrificial area (Fig. 1C).

On the basis of jade material identification, the provenance of the jade material could be further discussed. As the newly discovered jade artefacts were all determined to be made of nephrite as well, the nearby Longxi nephrite became the most likely provenance of Sanxingdui jade (Fig. 1B). The Sanxingdui site is located in the Chengdu Plain of Sichuan Basin, which is surrounded by great mountains on three sides and is close to the active fault zone of the Longmenshan Mountain Thrust Belt [40]. It was not easy for Sanxingdui people to transport large quantities of jade materials from the outside to the inside of Sichuan Basin. However, at the convenience of the Jian River, a tributary of Tuo River, it can be effortlessly transported to the Sanxingdui site. Besides, the Longxi nephrite is mainly green, thin-bedded (8–20 cm) and schistose with the preferred orientation of mineral grains. Though the lack of massive nephrite materials sets limits to carving colossal jade artefacts like statues, its thin-bedded structure and foliation make it easy to be quarried. In fact, among the 229 jade artefacts unearthed from K1 and K2, more than 90% are flat with a thickness of 0.5–2 cm, including 61 pieces of *zhang* forked blade, 77 pieces of *zao* chisel, 36 pieces of *ge* blade, 12 pieces of ring-shaped artefacts, several jade axes and beads. The same goes for these newly unearthed jade artefacts from pit K8. Thus, it suggests that the ancient Sanxingdui people might collect local Longxi nephrite and process them into certain jade artefacts.

Color alteration mechanism and burning sacrifice

Although the raw material is the same, the different color alterations ('*qin*' 沁) make the ancient jade characteristic. By comparing the pH values and elemental components of soil on layer No.6 and layer No.7, it is evident that the higher Fe content in soil led to the widely-spread red alteration. It is more convincing than merely comparing the element contents of color alteration areas and jade color areas. Both of the layers provided neutral burial environment with pH of 7–8, different from the former understanding of acidic soil in southern China [19, 26]. Therefore, it requires careful consideration to cite soil data for the color alteration research. Collecting soil data of archaeological sites during the archaeological excavations would be helpful to understand the mechanisms of jade color alterations and to distinguish the original jade color.

The Raman spectra showing thermal mineral phase transition from tremolite to diopside provide evidence of jade burning. Burning sacrifice called '*liao*'燎 was recorded on the oracle bones and burning jade activities was reported in the study of Fu Hao Tomb [24]. In Sanxingdui, it was under debate that the objects were burnt during the sacrifice or by invaders [41]. With the discovery of pit K3-K8, it's undoubted that these eight pits were sacrificial pits given the similar directions of all the pits and the similar combinations of artefacts inside each pit (Fig. 1C). In this case, the jade artefacts in pit K8 were burnt and buried by Sanxingdui people during sacrifice. In line with other clues such as the burnt earthen chunks and bamboo charcoals in the pit, the on-site non-destructive analysis is efficient to detect the existence of jade burning activities.

Identification of unique type through morphological database

Geographically isolated from the Central Plains where the political centers of Bronze Age China located, Sanxingdui formed and kept a relatively independent cultural tradition. The bronze vessels in Sanxingdui show significant similarity with those from Central Plains and the patterns which had never been seen before in Sichuan or anywhere else show distinctly local characteristics [38]. As for jade artefacts, the number of the *zhang* forked blade is sufficient, which is an ideal material to study the local characteristics of the shape and pattern in Sanxingdui. Yang (1994) argued that the Sanxingdui Type 1D was probably originated from the *ge* blade [42]. Traditionally, the categorization of jade artefacts is based on qualitative observation and empirical judgment, making some of this work controversial and comparative studies complicated. From the PCA analysis, the overlap of the morpho space of the *zhang* forked blades Type 1D and the *ge* blades from Sanxingdui pit K1 and K2 supported the argument of Yang (1994) in a quantitative way.

Although the *zhang* forked blade from pit K8 fell in the overlapped area of Type 1D and Type 2 C, it's obvious that it is a distinct type compared to those from other relatively contemporaneous sites. It is worth mentioning that Type 1D overlaps with *zhang* forked blades from other cultures, suggesting this type has higher comparability and potential to further the quantitative analysis in a large temporospatial framework.

Conclusion

The raw material for the newly unearthed jade artefacts from Sanxingdui pit K8 is green nephrite mainly consisting of tremolite, supporting the material and color preference in the ancient jade. By portable Raman and XRF spectrometers, the scientific evidence of jade burning during sacrifice in Sanxingdui was presented for the first time. It plays a key role to understand the sacrificial activities of Sanxingdui people during the Bronze Age. The mechanism of the red alteration color is related to the Fe^{3+} content in the surrounding soil based on comparing the elemental contents of both soil and jade artefacts. This broke through the method of comparing only the components of different areas on the jade artefacts. Relatively neutral environment with pH of 7–8 could be a factor that had decelerated the weathering rates. Further comparative studies require more soil data collected during the excavation. On-site geometric morphometrics analysis shows that the *zhang* forked blade in Sanxingdui pit K8 can be cataloged to the most typical Sanxingdui Type 2 C. This is a useful attempt to establish a database for jade artefact typology. In this way, all the jade artefacts could be scientifically identified and quantitatively characterized on site and added to the database before they were stored into conservation centers or museums.

It should be noted that this study has some limitations caused by the accuracy of portable Raman spectrometer and the lack of quantitative database of ancient jade artefacts. It suggests that more archaeological information is collected on-site during excavation in quantitative way.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-023-00960-1.

Additional file 1: Fig. S1. Orientations and landmarks of *zhang* forked blade for the geometric morphometric analysis. **Fig. S2.** The typical *zhang* forked blade for comparison. **A** Sanxingdui Type 1B; **B** Sanxingdui Type 1C; **C** Sanxingdui Type 1D; **D** Sanxingdui Type 2B; **E** SanxingduiType 2C; **F** Sanxingdui pit K1-2 *ge* blade; **G** Yanshi-Shangluo, Henan; **H** Shimao, Shaanxi; **I** Simatai, Shandong; **J** Southeast coast; **K** Vietnam. **Table S1.** Jade *zhang* forked blade and *ge* blade fromSanxingdui pit K1-2[1] involved in geometric morphometrics analysis. **Table S2.** Jade *zhang* forked blade from other localitions involved in geometric morphometrics analysis.

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Author contributions
HL Investigation, conceptualization, data collection, draft preparation. WLF investigation, methodology, raman and XRF analysis, writing—original draft preparation. SYX writing—reviewing and editing. JC visualization, PAC analysis, editing. HLR investigation, supervision, sample collection, writing—reviewing. YL investigation, supervision, sample collection, writing—reviewing. HZ: sample collection, writing—reviewing and editing. All authors read and approved the final manuscript.

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Availability of data and materials
All data analyzed in this study are included in the article. Detailed information see Additional file 1.

Declarations

Competing interests
The authors declare that they have nocompeting interests.

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