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Identification of a source of nephrite from late Shang Yinxu by multispectral imaging

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Abstract

The provenance of nephrite excavated from the capital of the late Shang dynasty is an important concern. Some nephrites with yellow-green color might have the same provenance. In this study, the provenance of three nephrite artifacts with yellow-green hue was determined by nondestructive multispectral imaging. The results show that they are very similar to nephrite from Xiuyan in northeastern China, suggesting that the Shang dynasty had some connection to regional cultures more than a thousand kilometers away. Of particular importance is the fact that the multispectral imaging method opens a new avenue for the study of the ancient jade circulation.

Keywords: Nephrite, Provenance, Yinxu, Multispectral imaging

Introduction

Having extensive traditional signification in the material, social and cultural fields, jade is both a treasure and an important manifestation of the splendid Chinese civilization. Due to the scarcity, purity, durability, and beauty of its raw materials, as well as its laborious and time-consuming production, jade symbolizes nobility, perfection, permanence, and immortality, and its use gradually became a representative of social differentiation and a carrier of spiritual beliefs [1, 2]. In the traditional conceptions, the term "jade" originally meant "beautiful stones", and nephrite stood out as the most highly valued jade. The conscious use of nephrite began in China about 9000 years ago [3]. After that, the exploitation, processing, and use of nephrite gradually became a symbol of the regime's control and power in allocating luxury resources [4]. Tracing the provenance of nephrite provides a wealth of information and clues for understanding the social complexity process, economic landscape, production management, and cultural exchange in ancient societies [5]. Therefore, the academic community has devoted itself to building a circulation network for jade, especially nephrite, and the results obtained so far are mainly based on the stylistic analysis of finished products. The foundation of the jade craft is the sourcing of raw materials, and if the framework of this ambitious plan is to be delineated, research into the provenance of nephrite itself is inevitable.

In the capital of the late Shang dynasty (ca. 1300–1046 BC), Yinxu, about 3000 jade objects have been found, including weapons, tools, ritual objects, ornaments, and decorative items, most of which are made of nephrite and represent a high point in the history of jade development [6, 7]. On the one hand, Shang nephrite wares consist of many heirlooms, including restored, remodeled, or redesigned jade heirlooms from a wide range of sources covering Late Neolithic cultures from different regions over the past 3000 years [8]. On the other hand, the Shang dynasty also possessed some of its own newly mined nephrites [9]. Initially, based on visual inspection and wishful thinking, many scholars believed that most of the Yinxu jade came from Hetian, Xinjiang, in northwest China (Fig. 1) [9–12]. Some even suggested the existence of a "Jade Road" as a prehistory of the "Silk Road" that bridged the material connections between Xinjiang and the Central Plains a distance of more than 3000 km [13].

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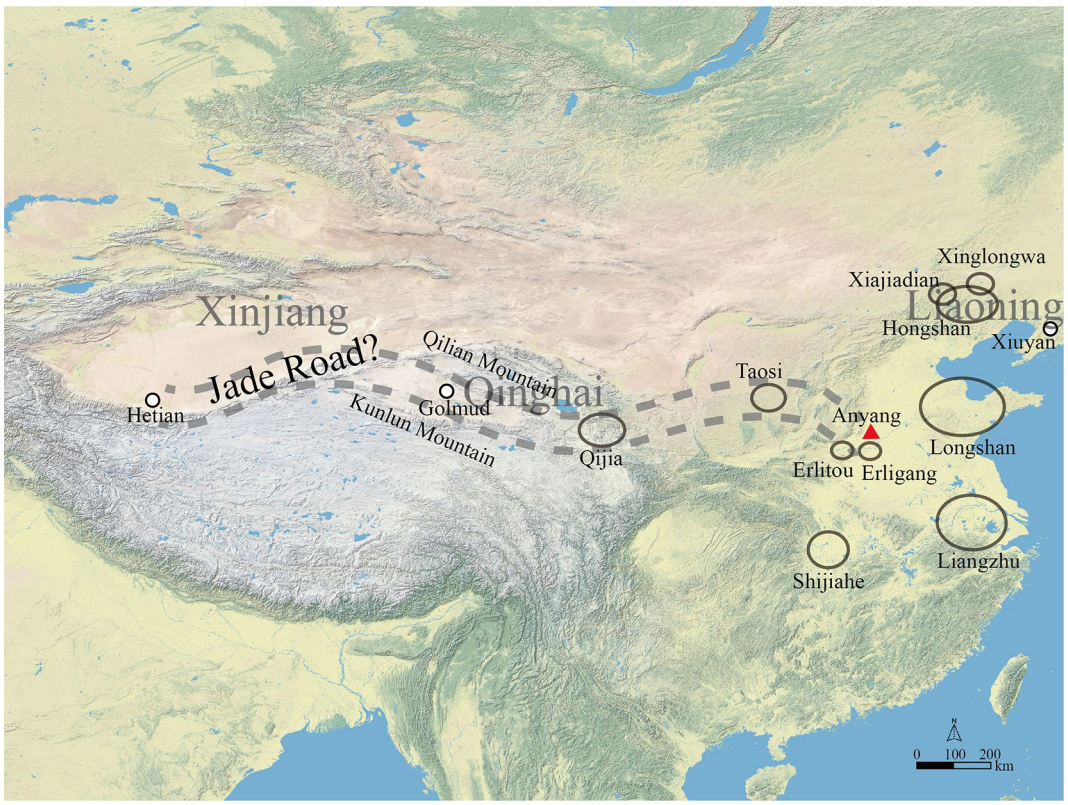

Fig. 1 Important regions of the ancient jade culture and modern nephrite deposits

Modern mineralogical concepts were not well known to Chinese archaeologists until the 1990s, and many scientific methods had not yet been established, which led many experts to tend to force a correlation between the category of excavated minerals and some known minerals mentioned in ancient texts. Thanks to the introduction of scientific instruments in archaeology in recent decades, recent studies have gradually moved away from the early purely visual examination and led to a clearer understanding of Yinxu jade materials [14–17]. Although some scholars still insist that some of the Yinxu jade originated from the legendary Kunlun Mountains (whose location in antiquity remains controversial, possibly in Xinjiang, Qinghai, or Gansu) (Fig. 1), a growing number of researchers are inclined to argue that long-distance transport of jade was not possible at this time, especially given the lack of much critical evidence along the presumed "Jade Road" and suggest that the source of the Yinxu jade should be narrowed down to the main control area of the Shang dynasty [18].

Determining the provenance of nephrite is a difficult task. According to geochemical theory, the microscopic fiber structure, trace element content, and isotopic content can allow conclusions to be drawn about the geologic setting and age of the nephrite mineralization, thus serving as a guide for determining its provenance. In recent decades, scientific research on nephrite, especially on the provenance of ancient jade, has essentially followed these ideas [19]. However, nephrite is a polycrystalline aggregate, which means that a number of indicators, such as chemical elements, associated minerals, and inclusions, overlap considerably between nephrite materials of different provenances. In addition, geochemical data (e.g., rare earth element distributions) for nephrite of the same provenance obtained by different laboratories sometimes differ significantly, e.g., using different scientific instruments and different test parameters, so they are not comparable [20]. Currently, only radioisotope dating methods (e.g. oxygen isotopes) are recognized as more accurate means of determining the provenance of nephrite [21]. However, invasive chemical composition testing and isotopic analysis are limited because cultural heritage investigations often require non-destructive techniques.

A fundamental feature of nephrite is its twisted-fibre microstructure, characterized by randomly-oriented felt bundles [22]. There are nuances in the structure caused by the crystallinity of the tremolite and the arrangement of the mineral particles due to different formation

conditions. These repeating features inside the nephrite can be referred to as submicrostructure because they are larger in extent than the microstructure. These visible features are often elaborated by connoisseurs and widely discussed in the market, and can provide clues to the provenance of nephrite [23, 24]. We have obtained good results in distinguishing the provenance of modern nephrite based on submicrostructure by multispectral image analysis, which opens new ideas for jade archaeology [25, 26]. In this study, this method was applied to ancient nephrite samples for the first time to re-evaluate the question of the provenance of a class of Yinxu nephrite and to further reveal the mineral flows in the context of our existing modern nephrite database and related archaeological data.

Material and method

Archaeological context and samples

Tomb M54 was discovered and excavated in 2000 and 2001. More than 210 pieces of jade were excavated in this tomb, which is the second largest quantity after the tomb of Fu Hao. The inscription "Ya Chang" on most of the bronze ritual wares indicates that the occupant of tomb M54 must be a leader of the "Chang" clan, and it is dated to late phase II of the Yinxu period [27].

Three jade artifacts were selected from tomb M54 (Figs. 2, 3), and their material was determined by infrared spectroscopy to be D-type nephrite, i.e. dolomitic marble-related nephrite [28]. They are translucent, as they are hardly affected by weathering. They have a bright yellow–green hue, show a very good sense of warmth and fineness, and are of high quality, usually without blemishes. Because of their similar colour and feel, it is often intuitively assumed that they have the same provenance.

The handle-shaped artifact (M54:398) is a particular type of jade object from the Xia, Shang, and Zhou dynasties. It is particularly abundant in the late Shang period, and was usually found in the tombs of high-ranking nobles in the capital of the kingdom. They usually consist of a narrow, rectangular body and a thin, short, sometimes pieced tang at the bottom; some even have a scabbard, and most are of small weight and size [29]. Arrowheads belong to the category of weapons, and this type of arrowhead made of nephrite is also a characteristic feature of the Yinxu culture, which, although not practical, reflects the dignified status of the tomb owner. Samples M54:364 and M54:366 represent exactly two different types of arrowheads. The former has an elongated shaft at the lower end that can be inserted into a groove, while the latter has a recessed notch in the axis of symmetry and has a perforation that allows the rope to anchor and secure itself. From the type and style of these objects, it can be concluded that they were processed in the late Shang period.

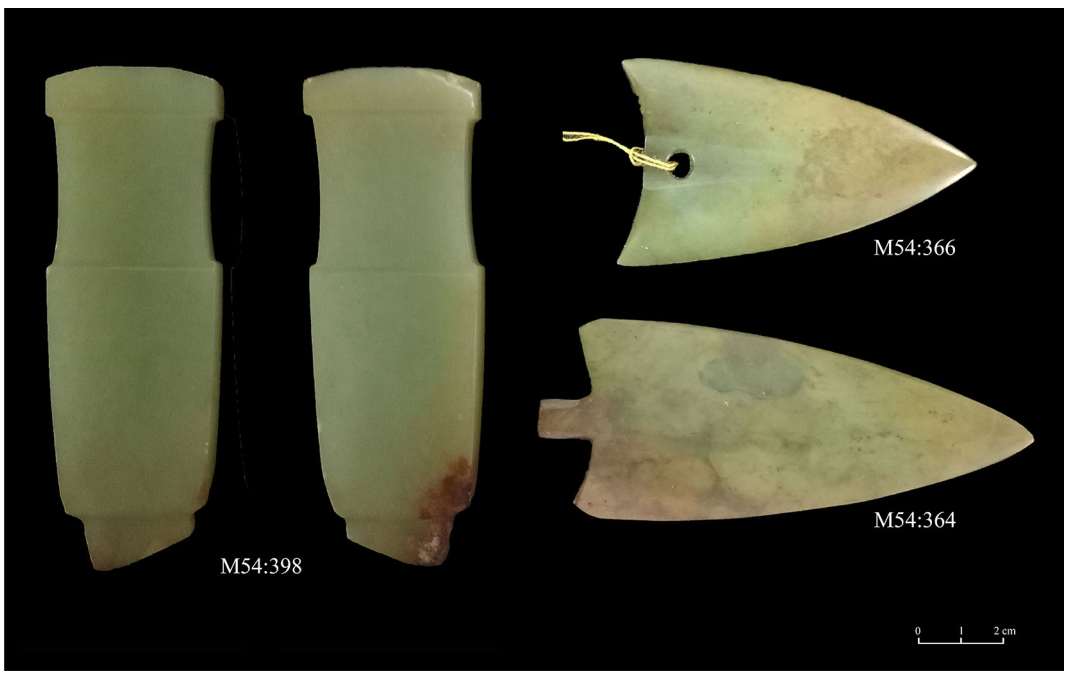

Fig. 2 Three nephrite artifacts with yellow-green color from Yinxu (both sides of the handle-shaped nephrite artifact M54:398, nephrite arrowhead M54:364, and M54:366)

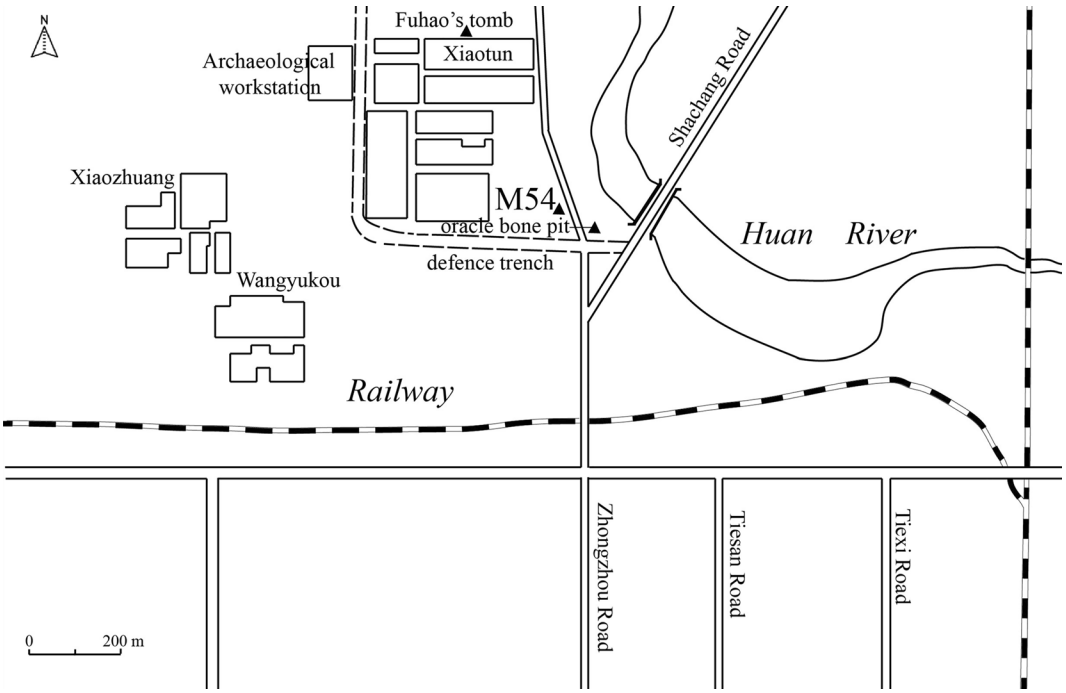

Fig. 3 The location of M54 in Anyang

Based on several reasonable assumptions about the availability of jade and considerations of its quality, nephrite from Xinjiang, Qinghai, and Liaoning has always been considered the most likely material for the production of ancient jade from Yinxu, which is why we made it the focus of comparative study. Modern samples closer in color to the yellow-green tones of Yinxu jade are selected for comparative study as much as possible. To ensure that they are all D-type like the ancient jade, the selected samples were tested with pXRF for a composition of Mg/(Mg + Fe) well above 0.93 [2] (Additional file 1: Table S1).

Method

It is important to emphasize that multispectral imaging is a method for detecting features of nephrite used by traditional visual methods. So far, the structural features of nephrite have been commonly used in the market, but the terminology used by different people is inconsistent, and some connoisseurs or folk experts borrow a lot of metaphorical rhetoric to describe the characteristics of nephrite as they see them, and these experiences can lead to some misunderstandings or errors when they are disseminated. As a result, many visual studies of nephrite have taken on a strong occult flavour and are often popular among a large group of Chinese folk connoisseurs, which in turn can cause many researchers to deliberately avoid them. Although these subjective experiences have actually had a positive effect on advancing jade research, they have not yet been rationally interpreted, much less confronted by scientific research. The scientific recording of images of nephrite features is sufficient to break through this limitation and closure, providing a common ground and basis for discussion for all and another way to solve the problem of determining provenance.

In this study, the CRi Nuance imaging system (USA) was used. The images are acquired in the wavelength range of 450–740 nm with a scanning step of 10 nm, covering the visible (VIS) and near-infrared (NIR) regions. The general experimental procedure is as described in our previous articles [25, 26], with some exceptions highlighted here for archaeological samples. The main operational improvement is to place the light source under the sample, i.e., to illuminate the sample transmissively instead of picking up scattered or reflected light (Fig. 4). Archaeological samples must be non-destructive, and no risky tests should be performed. In our multispectral experiments, although there is no direct contact with the sample, too much light can lead to high temperatures that can change the properties of the sample due to the light source that must pass through the sample. For this reason, transmitted light produced by light emitting diodes (LEDs) is used to illuminate the sample instead of halogen lamps and other variable light sources. The sample was placed on the support platform at the correct height and angle to ensure that it is within the field of view of the objective. To avoid stray light, an enclosed space is

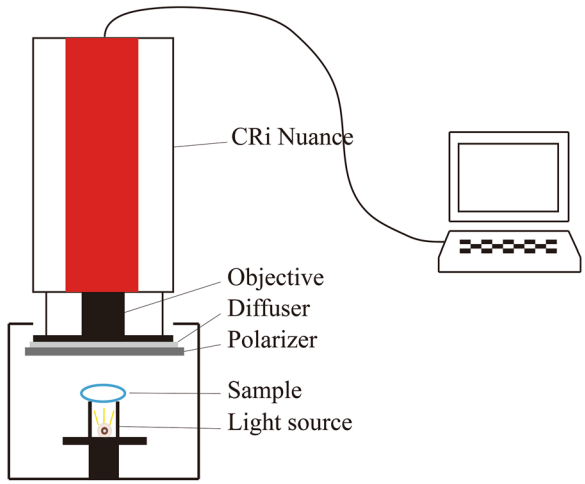

Fig. 4 The experimental system for recording multispectral imaging

constructed around the specimen to serve as a darkroom. The distance between the flat surface for all of samples and the lens is the same, the depth of field of focus will be consequently easier to be determined. The focal length of the lens was then adjusted until the image of the sample was clearly shown. The exposure parameters were preset and self-adjusted and the images will be recorded and saved by software.

It is apparent from a series of multispectral images that each image receives a different amount of light energy. With the increase of wavelength, the image gradually changes from dark to light and then from light to dark. When the light wavelength is about 600 nm, the brightness of the image will reach the highest. In most cases, the area with 0 grey level is the background which need to be discarded, whereas the brightest area is also invalid due to the high intensity of illumination. If there is an area with grey level higher than 230, the observation will be affected. Hence, if the overall grey levels were set up more balanced, the original image will contain more details and gradations. Based on the above reasons, the moderate image of band 660 nm is selected as representatives in each series, and at the same time, the band of 510 nm could also be chosen due to symmetry presented by the multispectrum [26].

Furthermore, to make the target features clearer, an idea of subtracting the fitted light distribution image from the original image (660 nm band) was adopted. Here a smoothing linear filter was applied to simulate the light distribution. As a low-pass filter, it has the net effect of blurring or smoothing the image, e.g. bridging small gaps in lines or curves. The value of each pixel in the image is replaced by the weighted average value which is the intensity levels in the neighborhood defined by the filter mask, this process will reduce abrupt transitions in an image [30]. After many trials, a filter mask of 40×40 was chosen for the linear filtering, which greatly enhances the visual effect without deviating from the original image features [26].

Results

Before turning to the archaeological samples, let us review the typical pictorial features of the modern samples to establish a basic reference system. Figure 5 lists the modern samples with typical structural features from each provenance. The distinctive features of nephrite from these provenances have already been described in detail by some scholars [24] (Table 1). Multispectral images can directly show the submicrostructure with grayscale differences due to the different spectral characteristics of some heterogeneous structural units. The structural units of nephrite are usually characterized by slightly lighter areas that stand out from the gray scale of the background. The textural units are grouped together in various sizes, shapes, and distributions to give a complete picture of the submicrostructure. In this way, the difference in submicrostructure can be intuitively understood as a difference in the distribution of textural units. The submicrostructure of the identical sample is the same, but may be different due to some imperfections of the nephrite (e.g., cleavage, fractures, envelope, etc.).

In terms of surface details, Qinghai nephrite generally has a faint oily luster, some of which is waxy and faintly vitreous glassy, but it is generally more transparent than nephrite from the other two sources [23, 24]. In addition, its submicrostructure has many bright spots with very low granularity in uniform and compact distribution (Fig. 6). This feature is mainly similar to granulated sugar, which explains that the submicrostructure is called "granular scattering". The situation is more complex for Xinjiang nephrite, whose mineral grains are very small, mostly in the form of microscopic crystalline and microscopic cryptocrystalline grains, while coarse crystalline grains are rare, so it appears slightly transparent and has a rather strong oily luster [23, 24]. The most important submicrostructure of Xinjiang nephrite is the "flocculent texture", the entire area of which has a fine-grained, velvety texture, or areas of alternating, evenly uniformly shifting clusters of light and dark grays, which appear either very uniform throughout or as a large continuous area of the same grays (Fig. 7). There are also some fairly high quality specimens that seem to be fine with fine textures or solid colors (Fig. 7). It should be noted that some of the highest quality nephrites, such as the top quality Hetian jade, have a very regular and dense arrangement of crystal fibers, making their submicrostructure almost uniformly gray. Liaoning nephrite always has a distinct

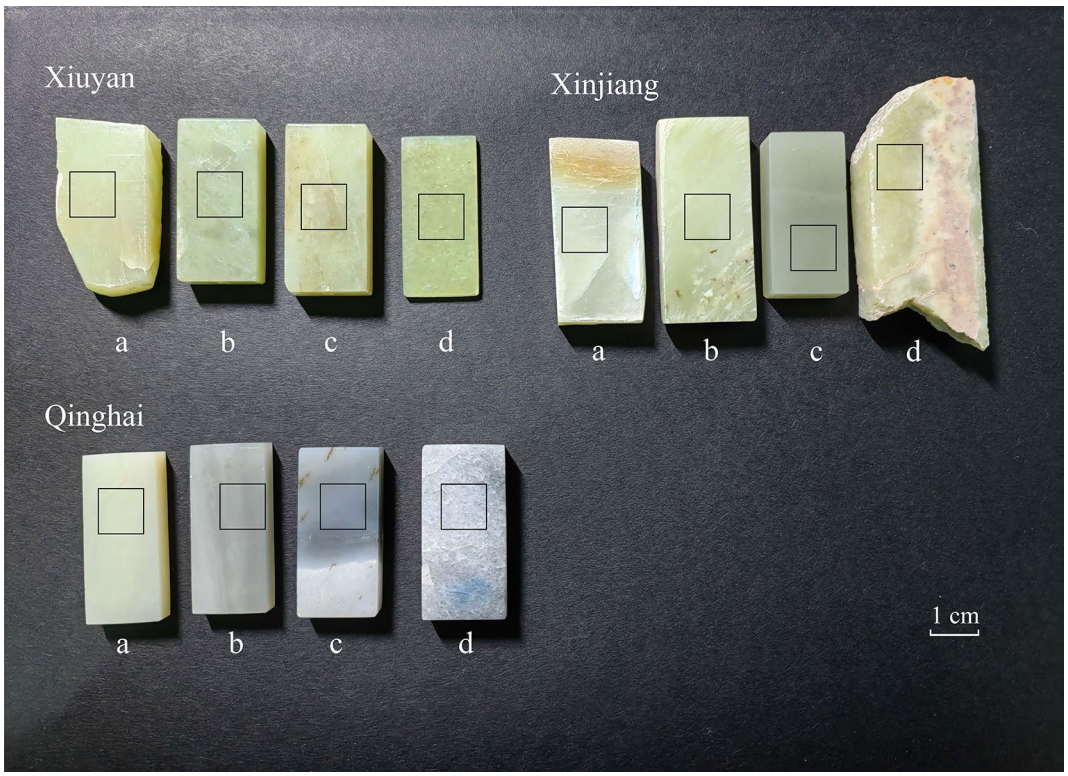

Fig. 5 The typical modern nephrite samples from Xiuyan, Xinjiang and Qinghai (The frame indicates the detection part)

Table 1 Comparison of the visual identification features of the nephrite from three sources

	Xinjiang	Qinghai	Xiuyan
Lustre	Strong grease gloss	Glass-wax gloss	Grease gloss
Transparency	Slightly translucent	Semi-translucent and uneven	Slightly translucent
Submicrostructure	Flocculent textures	Granular scatter	Blurred pieces
Size	> 0.8 cm^2	0.05 ~ 0.1 cm^2	> 0.8 cm^2
Distribution of textural units	Comparatively regular	Uniform	Slightly disorganized

oily luster and is predominantly translucent [23, 24], with a submicrostructure of "blurred pieces" containing faint lighter but contiguous areas larger than 1 cm^2. Closer inspection reveals that the different highlighted areas are not at the same depth within the nephrite, but belong to separate mixed layers (Fig. 8).

For the archaeological samples, the current imaging results are clearly comparable to modern nephrite materials (Fig. 9). These three Yinxu nephrite specimens are generally unaffected by cracking, do not exhibit particularly pronounced grayscale differences, and yet reveal some internal structural features through differential light transmission. There is neither excessively fine and dense submicrostructure nor bright granular submicrostructure, but only relatively randomly highlighted patches of large size, and these patches do not appear to be on the same plane, as judged by depth of field. Several features suggest that these samples are more likely to be nephrite from Liaoning.

There are also comparative analyses according to conventional visual characteristics, for example, the very important factor of color, which in practice is mainly called hue. This is because in a non-monolithic mineral such as nephrite, not every indicator can be completely uniform, and graded hues often cannot be readily represented in an absolute color system. The various inhomogeneous features or variations can be viewed as an intrinsic characteristics that are necessarily linked to

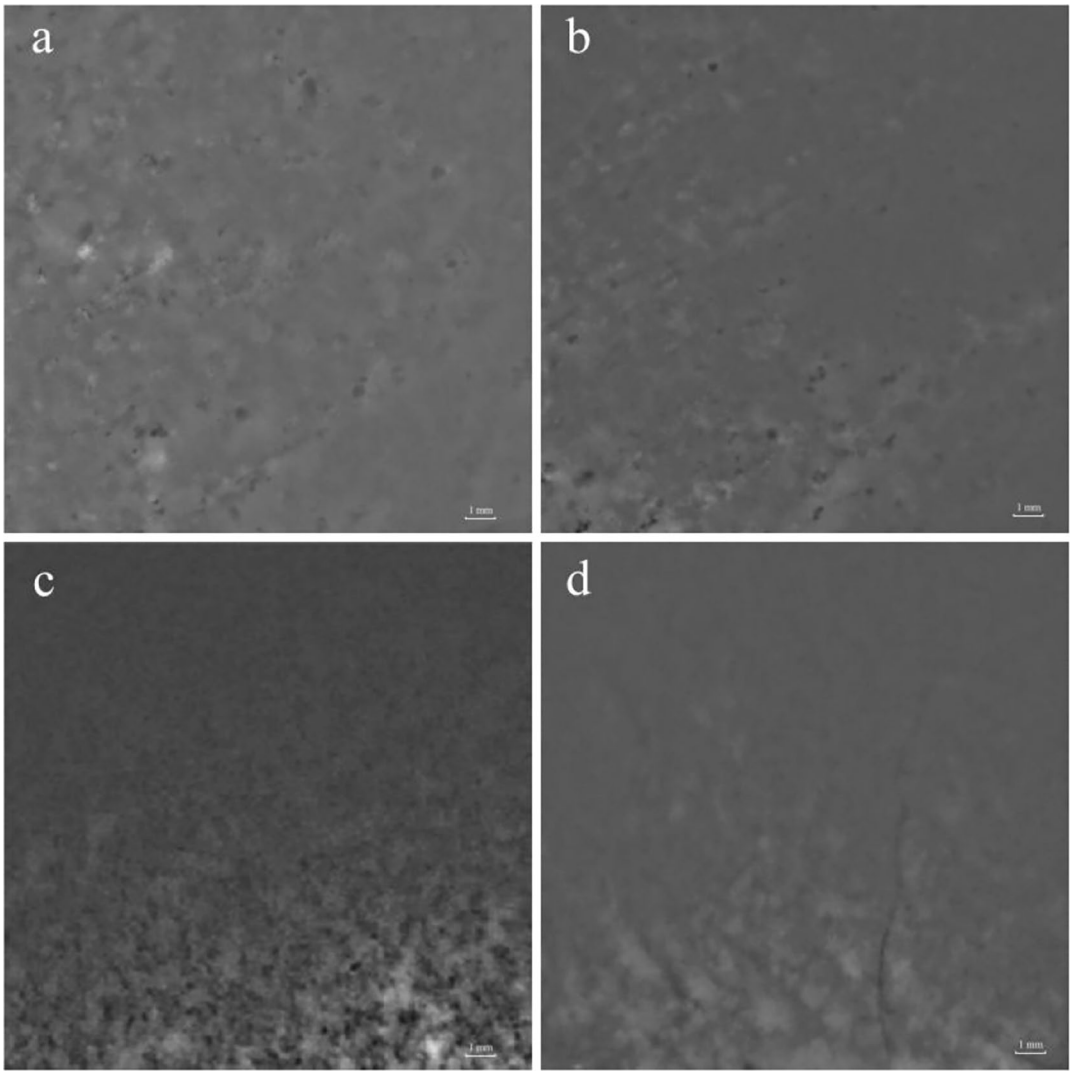

Fig. 6 The submicrostructure of Qinghai nephrite

the mineralization process and the environment of the occurrence, and although this linkage may require several logical chains to connect them, it may also be indicative of provenance characteristics [24, 25]. In this sense, the pale greenish-yellow color of these nephrite objects hardly appears to be nephrite from Xinjiang or Qinghai. In addition, the handle-shaped object exhibits a deep red secondary coloration on the upper surface, a signature that occurs only after a long immersion of iron ions in the water, suggesting that it was made from a nephrite pebble. The two nephrite arrowheads also exhibit a slightly lighter, but also red secondary color. It is known that a type of nephrite pebble known as "river-grinding nephrite" in Xiuyan, Liaoning, also has such characteristics and has a long history of development. Many of the ancient nephrite objects from the Hongshan culture still have the red colored crust of the "river-grinding nephrite" [19]. Previously, scientists had conducted a comparative study between modern and ancient nephrite objects and found that the yellow-green nephrite with red crust from Yinxu occurs in very similar form in Xiuyan nephrite [19]. Old and new evidence now suggests that the nephrite material used to produce these specimens originated in Liaoning.

Discussion

The provenance evidence of the analyzed nephrite objects indicates that Xiuyan, Liaoning was most likely connected to the Shang dynasty in a subtle way. Regardless of whether these nephrite objects were remodeled

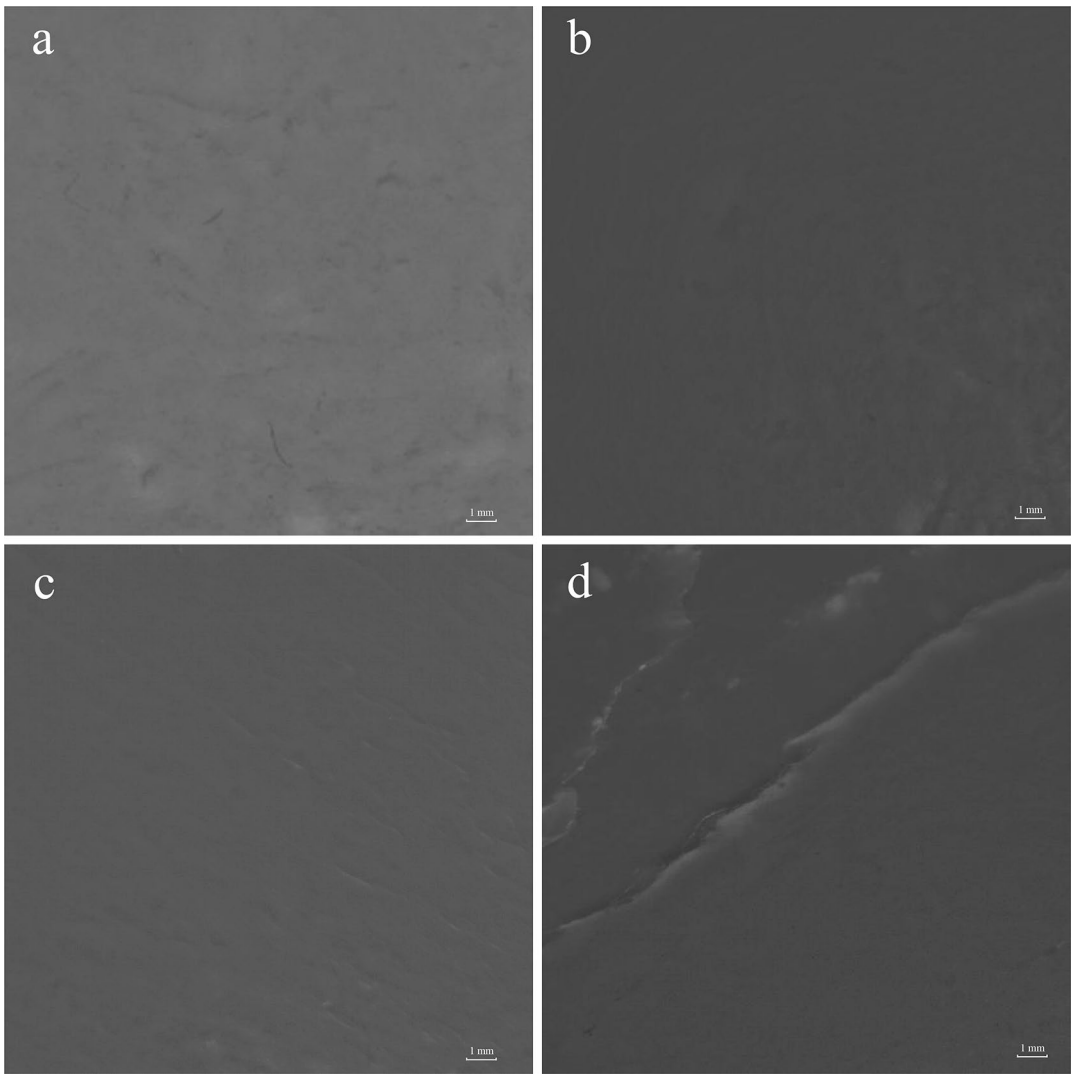

Fig. 7 The submicrostructure of Xinjiang nephrite

from relics of earlier dynasties or cultures in northeastern China or were made directly from raw materials extracted at that time, they would indicate that nephrite from Xiuyan had already reached the craft workshops of the Shang royal court. This extensive access to resources could be the result of direct control by the Shang dynasty, a series of material exchange chains, and, of course, tributes to the royal court. But the specifics of the situation require not only a detailed study of the jade from Yinxu, but also an examination of the provenance of the raw material as well as the broader context, and in particular the possibility that the chronological sequence of objects may correspond to specific events should be considered.

Aside from the form in which material materials circulated, the evidence from the Lower Xiajiadian culture (c. 2000–1500 BC) fill an important missing link in the association of the Shang dynasty with northeast China. Based on the heritage of the local Neolithic archaeological culture, the Lower Xiajiadian culture absorbed various factors such as the Erlitou culture, the Pre-Shang culture, and the Yueshi culture, and became the archaeological culture with the highest level of development in northeast China at that time and the earliest entry into the Bronze Age [31]. The developed divination and painted pottery of the lower Xiajiadian culture also spread to the Central Plains. As for the jade objects, the penannular jade pendants, jade ornaments with cloud and hook pattern, jade notched discs found in the Fu Hao Tomb at Yinxu in the late Shang dynasty belong to the typical jade style of western Liaoning, which

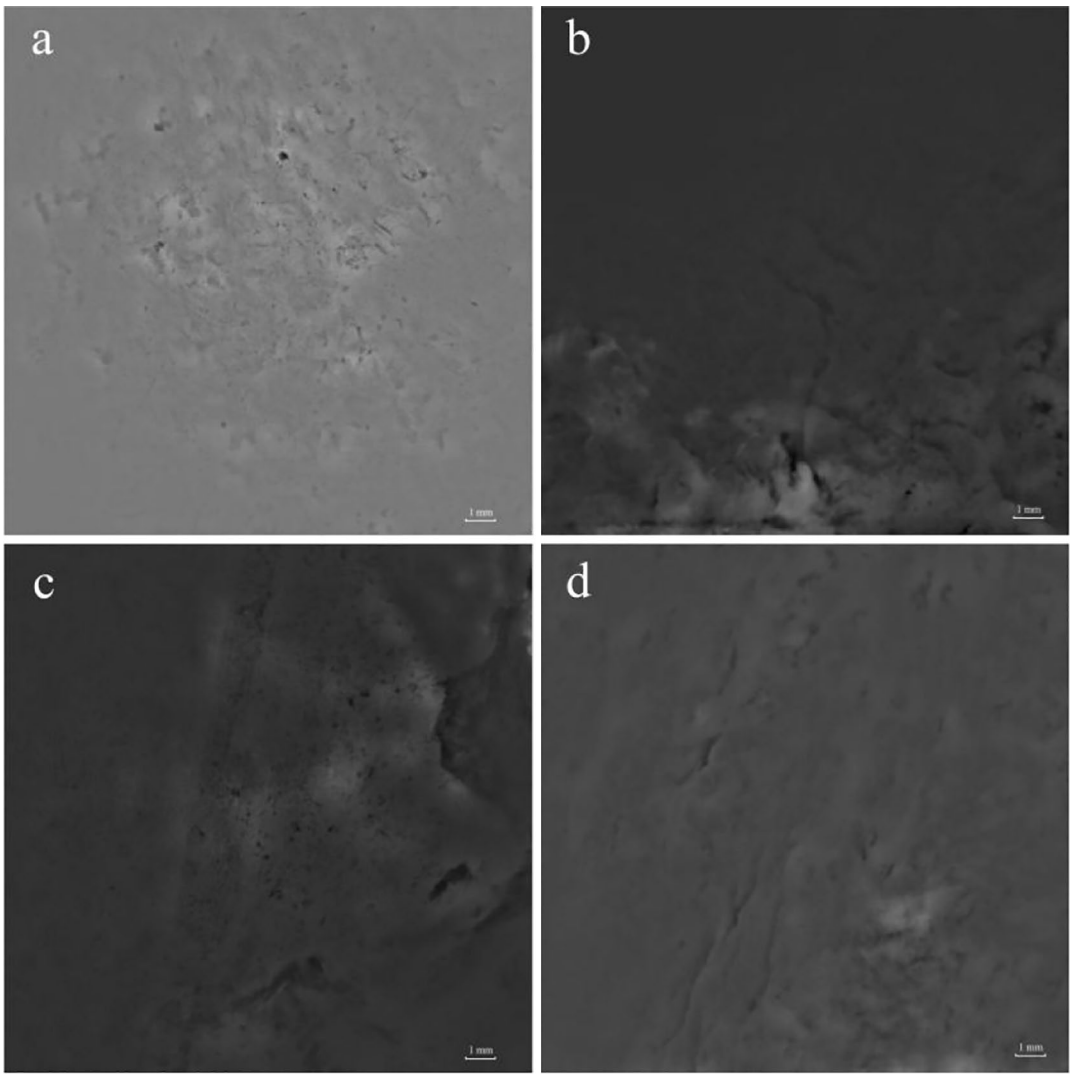

Fig. 8 The submicrostructure of Liaoning nephrite

may be among the jade relics of the northern steppe region acquired from by the Lower Xiajiadian culture and imported to Yinxu [8]. Moreover, the bronzes of the Lower Xiajiadian culture and the Yinxu culture have been detected as containing similar highly radiogenic lead [32]. Both jade and metal were very valuable at this time, reflecting the regime's ability to acquire resources and the extent of that power [8]. This coincidence seems to indicate a very close relationship between the two cultures. Another concurrent change occurred in the bronze culture of northeast China during the late Shang dynasty, such that distinct bronze mining and smelting sites emerged from this time onward, which includes a number of late Shang bronze artifacts excavated in western Liaoning, confirming some kind of exchange that continued between the Central Plains and northeast China [33].

The exploitation and use of Xiuyan nephrite occurred quite early. According to today's overwhelming knowledge, the main raw materials of nephrite artifacts of Hongshan culture also came from Xiuyan [34]. Some ancient legends say that there are actually mountains in this area where jade is extracted and Huainanzi of the Han Dynasty mentions the toponym Yiwulue as the place where a rare precious jade stone called Xunyuqi can be found. Many scholars have associated this ancient discovery with the nephrite of Xiuyan to confirm the reputation of the nephrite of Xiuyan and also to illustrate a strong continuity of knowledge about jade at that time [34]. Continuing this view, some evidence has slowly emerged

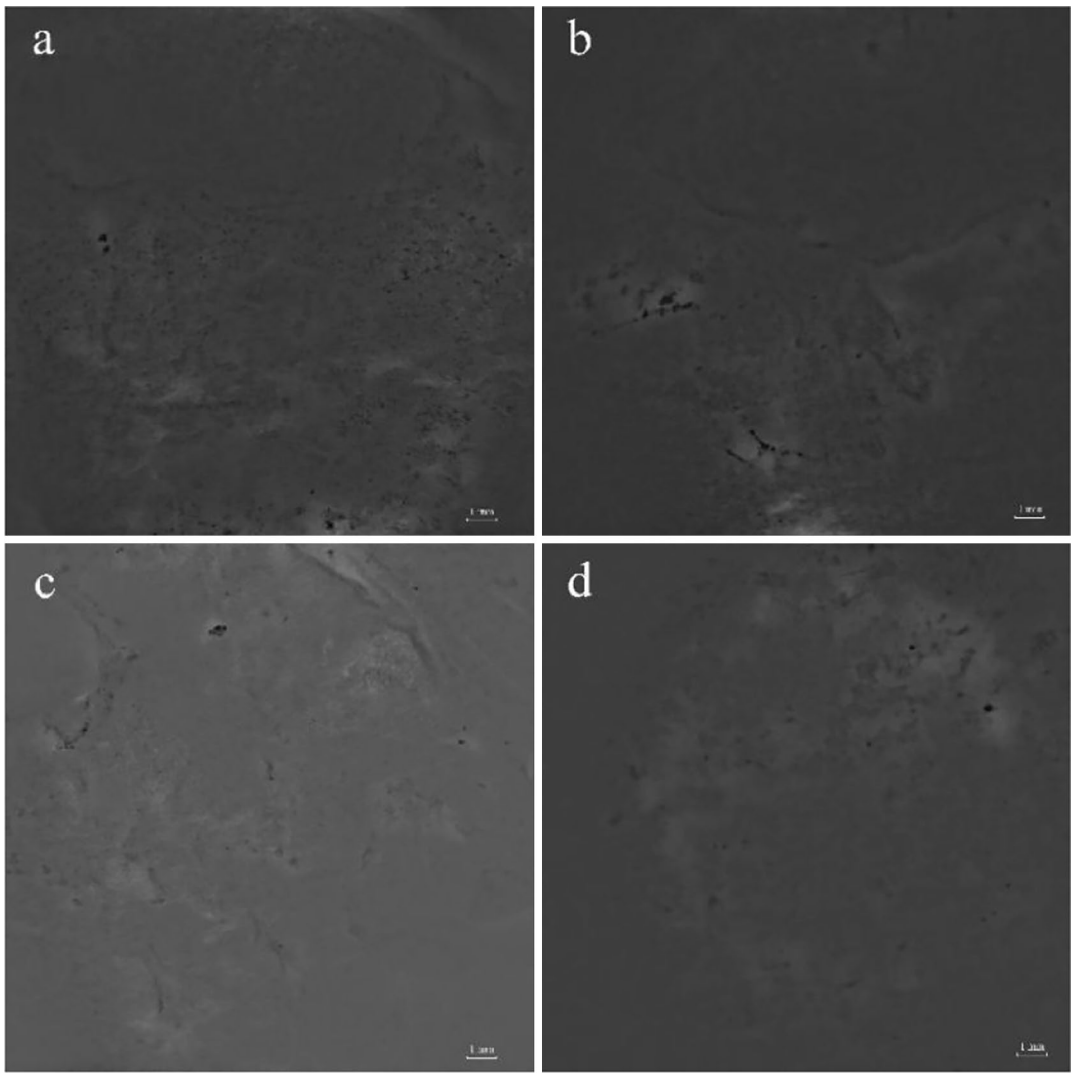

Fig. 9 The submicrostructure of Yinxu nephrite samples: **a** M54:364, **b** M54:366, **c**, **d** M54:398

that reflects some implicit links between the Yinxu culture and the Hongshan culture.

Primitive religious beliefs developed during the Hongshan culture period. The concepts of ancestor worship and dragon totem worship are already showing signs of maturity in the Hongshan period, and both of which were the main objects of sacrificial acts in the Shang Dynasty. For example, some openwork nephrite pendants in the shape of hooked cloud excavated in Fu Hao Tomb are direct remnants of Hongshan culture. Some other nephrite of curly-up dragons and figurines were heavily influenced by the Hongshan culture. An even more important fact is that the jade ritual system originated in the Hongshan culture and had an indelible influence on the jade beliefs and rituals of later generations [35]. Thus, there is now a view that the formation and development of Shang civilization and the origins of Shang culture are closely related to the Hongshan culture, and that even the ancestors of the founders of the Shang dynasty may have come from the Western Liaoning River basin [35]. If this is true, the situation became reasonable for the continued use of the same nephrite material as that of the Hongshan culture in the Yinxu period. Some scholars speculate that in ancient times, the extraction of jade was monopolized by fixed families and that the source of the jade material may have been a secret kept for generations. The nephrite objects from the Yinxu period may indicate that these families had not relinquished their hold on nephrite resources, perhaps still acquired from afar, or simply consumed from previous stocks [8].

Conversely, the claim that these yellow-green ancient nephrite originated from Xinjiang would contradict some existing archaeological data. First, the earliest nephrite artifacts in Xinjiang are only a few axes and pendants from the 1st millennium BC and the small quantity and coarse appearance can hardly match the size and beauty of Yinxu nephrite [36]. Other archaeological cultures along the so-called Jade Road from the 2nd millennium BC also did not possess nephrite of similar quality [13]. In particular, the Qijia culture in the northwest, the Taosi culture in the north, and the Erlitou and Erligang cultures, which predate the Yinxu period, excavated a number of nephrite objects, but they are of mottled colour and bear no resemblance to the samples presented here [18]. In all seriousness, of course, the evidence here only suggests that it is highly unlikely that this type of nephrite came from Xinjiang.

In fact, the great variety of jade objects from Yinxu can be considered as a collection of the great achievements of previous generations. For example, some studies on the stylistic analysis of the jade objects from Fu Hao Tomb have shown that some of them are from past archaeological cultures, including Xinglongwa culture, Hongshan culture, Lower Xiajiadian culture, Taosi culture, Longshan culture, Qijia culture, Shijiahe culture, Erlitou culture, Erligang culture, etc., which confirms the strong preference of the ruling class for jade and their great ability to acquire it (Fig. 1) [8]. Some nephrite objects, on the other hand, show strong inspirations from certain earlier cultures, such as the jade cong-tubes influenced by both Liangzhu culture and Qijia culture, indicating the eclectic nature of jade styles at that time [37]. The prehistoric jade cultures were largely represented in different regions due to the geographical distribution, and it was not until the Shang dynasty that the various jade artifacts concentrated like a vortex in the Central Plain, and the production ideas of some regional cultures converged in the core of the Shang dynasty, even without physical input [13]. The Shang dynasty not only sought complete jade artifacts, but also procured new jade resources from various places to satisfy their own ritual and aesthetic needs.

Since nephrite could be easily passed on to later generations, the time span of the circulating exchange network of finished nephrite objects may have been quite long. However, tracing the provenance of culturally typical nephrite objects is another matter, and it is possible to reveal the interactions between forces through a higher resolution chronology. The examples in this paper demonstrate the implicit relationships that still existed between the late Shang culture and the Northeast, particularly the Liaoning region, even during the Yinxu period.

Conclusion

The question of the provenance of ancient jade materials has always been a necessary prerequisite for jade research, but has remained unresolved until now. Here, for the first time in ancient jade research, we employ non-destructive multispectral imaging to determine the source of the raw material. This method directly dispalys images of the submicrostructure images to highlight features that indicate the provenance of nephrite. Three very well-preserved and exquisite nephrite objects with greenish yellow hue were carefully examined and compared with similar modern nephrite samples from three possible provenances. We concluded, that the three Yinxu nephrite pieces are Xiuyan nephrite. Possible connections to the Hongshan culture are also specifically discussed.

This artical demonstrates the great potential of multispectral imaging in studying the provenance of jade. What we can expect in the future is the use of some pattern recognition and artificial intelligence algorithms to distinguish the features of different images and then build an automatic processing system. As mentioned earlier, the jade from Yinxu is very diverse, both in terms of mineral material and the different visual features. The present work is just the beginning, and further detailed studies of the nephrite will gradually reveal the mystery of the Yinxu jade source. In addition, for a large number of ancient nephrite artifacts, we will be able to answer the fundamental question of their provenances by adding more modern samples to the database.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-022-00849-5.

Additional file 1: Table S1. Portable XRFresults of chemical composition of the modern nephrite samples from differentprovenances (%).

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Author contributions

DC performed the data analysis. DC and YY were major contributors in writing the manuscript. JT provided the archaeological context. MY provided the modern samples. DC, YY and CW designed the method. All authors read and approved the final manuscript.

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Availability of data and materials
The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

Competing interests
The authors declare no competing interests.

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