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Investigation of a simulated Chinese jade and bronze dagger-axe by neutron radiography and prompt gamma activation analysis

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ABSTRACT

In ancient China during the Shang dynasty, ca. 1600 BCE–1046 BCE, intricate jade and bronze dagger-axes (*ge*) were made and used by the elite as ritual symbols of power and prestige. These meticulously crafted ceremonial weapons consist of a nephrite jade [$Ca_2(Mg, Fe)_5Si_8O_{22}(OH)_2$] blade mounted in a bronze haft. Several examples of these dagger-axes are included in collections in the United States. There has been recent interest in applying neutron radiography to image the jade tang hidden within the bronze haft and uncover early manufacturing techniques. As a preliminary test of feasibility, a simulated dagger was made using a modern replica blade carved from nephrite from Wyoming, USA, and copper alloy plates. The simulated dagger was first imaged by X-ray and neutron radiography at the NIST Neutron Imaging Facility. The details of the jade tang within the copper alloy haft were clearly visible. Subsequently, the nephrite blade and the copper alloy plates were analyzed by cold prompt gamma neutron activation (PGAA) to evaluate the feasibility of this technique for identifying the nephrite source. The PGAA was performed at the Cold Neutron PGAA station at NIST. Three nephrite specimens in the Smithsonian collection from China, Siberia and Taiwan, characterized previously by electron microprobe analysis, were used as comparative standards. The major nephrite elements - Ca, Mg, Fe and Si - were analyzed with uncertainties in the range of 0.3%–0.4%. Three of the trace elements conventionally used for sourcing, Cr, Mn and Ni, were analyzed with similar uncertainties. The residual radioactivity of the objects was below the NRC exempt limits.

1. Introduction and research questions

The Shang dynasty, ca. 1600–1046 BCE, is the earliest Chinese dynasty for which written records survive (Thorp, 2006). Its territory lay in northeast China along the Yellow River with the capital near the modern city of Anyang. One of the premier weapons during the Shang dynasty was a dagger-axe (ge), illustrated in Fig. 1, a pole-mounted weapon with a dagger-shaped blade and tang mounted through a perpendicular wood or bamboo shaft. The earliest dagger-axes were made of stone, but later versions were cast in bronze and used on the battlefield (Hong, 1992). Rare examples were made with jade blades and inlaid bronze hafts and likely served a ceremonial function, possibly used by the elite as ritual symbols of power and prestige. Several examples of these unique jade and bronze dagger-axes are held in museum collections in the United States, including the Smithsonian Freer Gallery of Art and Arthur M. Sackler Gallery, the Harvard Art Museums and the Asian Art Musuem.

Constructing these composite weapons involved workshops for bronze casting and stone carving. The jade blades were carved with a thin tang protruding from the rear, and the bronze hafts were cast with a corresponding slot for the jade tang. No surviving records describe the workshop production and manufacturing methods of these complex objects. Studying the internal structure of the jade blade and bronze haft, and how closely their shapes align, could lend insight to the mold-making process, production order, and how the distinctive elite craftsmen of the Shang dynasty collaborated on composite objects. However, the region where bronze overlaps jade cannot be examined by conventional X-ray radiography, a method available to many

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Fig. 1. Jade Dagger (*Ge*), Late Shang Dynasty, ca 1300 BCE–1050 BCE Freer Gallery Accession Number: S1987.898.

institutions for examination of artwork, because the electromagnetic X-rays are highly attenuated by the outer covering of bronze. The shape of the bronze slot is visible, but the corresponding size of the jade tang cannot be seen.

For X-rays the attenuation occurs primarily by Coulomb interactions in the electron cloud around the nucleus of the atom. The number of electrons increases with atomic number which correlates with physical density. Thus, the X-ray attenuation cross-section increases monotonically with density. However, neutrons interact only with the nucleus itself. The neutron attenuation coefficient can vary significantly from one element to the next, or even among isotopes of the same element. Consequently, neutrons could penetrate easily through the bronze but could be attenuated by the light elements, particularly hydrogen, in the jade. Therefore, it was decided to evaluate the feasibility of neutron radiography for visualizing the concealed features of the tang/haft attachment.

Since it is necessary to bring the dagger to the nuclear reactor for neutron radiography, this provides the opportunity to utilize another reactor-based method, namely prompt gamma neutron activation (PGAA, formerly PGNA) to carry out an elemental analysis of the jade dagger. When a neutron is captured by a nucleus, gamma rays are emitted with characteristic energies. Thus, the gamma ray energy spectrum of a material being irradiated by neutrons can be used to identify its elemental composition. The effectiveness of the method depends on several intrinsic properties of the isotope of interest including its neutron capture cross section, its isotopic fraction and the gamma ray yield. The practical measurement issues also include the material's attenuation of the incident neutron beam and the emitted gamma rays.

The term “jade” has been applied to two different minerals (Harlow and Sorensen, 2005). Nephrite is a microcrystalline form of calcic amphibole which has the formula $Ca_2(Mg, Fe)_5Si_8O_{22}(OH)_2$. A major source area has been the Kun Lun Mountains in the Xinjiang region of western China. Other sources are Kazakhstan, Siberia and Taiwan. Ancient Chinese jade objects were made exclusively of nephrite. However, during the reign of the Qianlong Emperor (1735 BCE–1796 BCE) jadeite from northern Myanmar became popular. This is a pyroxene with the composition $Na(Al,Fe^{3+})Si_2O_6$.

Bronze is primarily copper alloyed with various elements, mainly tin and lead. Ancient Chinese bronze typically also had some trace elements including Fe, As, Sb, Zn, Au, Ag and Co (Holmes and Sayre, 1995)

In addition to providing insight into the method of the attachment of the blade to the haft, neutron methods could also be applied to other archaeometry issues concerning the dagger axes and other jade and bronze objects. These include the source of the jade and the composition of the bronze. Finally, it has been proposed that heat treatment of the jade may have been occurred before carving or during burial rituals in antiquity, as well as used in the production of modern forgeries (Douglas, 2001).

The possible application of neutron analytical methods to these archaeometry topics raises a number of research questions on their feasibility. For the imaging techniques these questions include whether there was enough contrast in the attenuation between the jade and the bronze to make visible the details of the attachment, the magnification required to resolve these features and the time necessary to obtain a usable image. For PGAA, it was the possibility of excessive deadtime, the set of elements that could be detected and the calibration method for converting gamma-ray counts into elemental concentrations. Finally, the exposure of the objects to neutrons inevitability raised the question of residual induced radioactivity. In particular, the bronze contains traces of cobalt and antimony which have relatively long-lived gamma emitting radionuclides that are above normal natural radiation background, raising health or environmental concerns over long term. As a preliminary test to address these questions without irradiating any authentic dagger axes, it was decided to test the methods on a jade and bronze mockup.

Fig. 2. Dagger axe mockup.

2. Methods and materials

2.1. Dagger mockup

The simulated dagger is shown in Fig. 2. It was made using a modern replica blade carved from nephrite from Wyoming, USA. The blade shape is a composite from several dagger-axes in the Harvard Art Museums' collection, and the elliptical shaped tang matches a dagger-axe with a visible tang in the Avery Brundage Collection at the Asian Art Museum in San Francisco (Object Number B60J907) with a thickness of roughly 0.3 cm. There was not enough lead time before the available dates at the Neutron Imaging Facility to cast a haft with a composition matching ancient Chinese bronze. Consequently, this was approximated by a stack of four rectangular plates 5.2 cm × 6.1 cm × 0.16 cm cut from a sheet of Cu-alloy metal in the study collection at the Smithsonian American Art Museum, originally from an early 20th-century architectural door kickplate. Preliminary XRF analysis indicated that it had significant zinc content which would make it a brass rather than a bronze. However, for the purpose of evaluating the feasibility of neutron radiography on a bronze haft, it is still usable because the attenuation is dominated by Cu with a factor of $0.072\ cm^{-1}$ compared to $0.006\ cm^{-1}$ for Sn and $0.019\ cm^{-1}$ for Zn. Finally, a length of fine silk thread was wrapped around the tang to simulate an attachment technique that was observed in a pseudomorph on a bronze dagger-axe in the Harvard Art Museums' collection.

2.2. Neutron and X-ray radiography

The radiographic imaging was performed at the Neutron Imaging Facility (BT2) at the NIST Center for Neutron Research in Gaithersburg, MD. This facility is equipped with both neutron and X-ray systems for simultaneous radiography or computed tomography (LaManna et al., 2017) as illustrated in Fig. 3. However, the two systems are oriented perpendicular to each other, and the planar geometry of the dagger made simultaneous radiography operation impossible. Therefore, the X-ray and neutron images were taken sequentially.

The dagger was first imaged by X-ray radiography. The beam was produced by a microfocus (13 μm–20 μm spot size) X-ray generator with