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TECHNICAL AND CONSERVATION STUDY OF A BRONZE MIRROR FROM ANIBA, LOWER NUBIA, EGYPT

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ABSTRACT

This research case study aims to investigate and conserve an ancient mirror excavated from the Aniba archaeological site located in Aswan, Egypt, dates back to the New Kingdom (16^{th} – 11^{th} c. BC). The mirror was in a poor condition and required cleaning and conservation treatments. The mirror was analysed using a multi-technique approach, including radiography, stereo microscopy, metallography, multispectral imaging, XRD, and p-XRF. The XRF results indicated that the mirror is made of a copper alloy (tin bronze). XRD indicated the presence of various corrosion products, including cuprite (Cu_2O), malachite $Cu_2(CO_3)(OH)_2$, atacamite $Cu_2Cl(OH)_3$, and paratacamite $Cu_3(OH)_6Cl_2$, in addition to Quartz (SiO_2), which together indicate the intensity of corrosion. The main objectives of this study are to assess the condition of the mirror, identify the corrosion and damage that have compromised the mirror and to find the most suitable method for conservation. In this contribution we review the history of the mirror, its condition, the documentation and cataloguing processes, and conservation procedures. The investigation concludes with preservation and storage recommendations.

KEYWORDS: Aniba, Egypt, New kingdom, Mirror, corrosion, investigation, analysis, conservation, storage

1. INTRODUCTION

Aniba is located in Lower Nubia, about 230 km south of Aswan (Fig.1). Currently under the waters of Lake Nasser, the site was an important city in antiquity, strategically located in one of the most fertile regions of Lower Nubia (Steindorff, 1935). It is one of the major sites testifying to Egyptian presence in Lower Nubia from the late Middle Kingdom to the New Kingdom and beyond (Näser, 2017). The bronze mirror (case study) is dating back to the New Kingdom.

As objects react to archaeological burial and post-excavation conditions, degradation occurs (Fig. 2). The preservation characteristics of metal objects found from archaeological sites are determined by the metal nature of the object and the surrounding environment (Casaletto, 2017; Ghoniem, 2011).

Archaeological metal artefacts that have been buried for a long time are subject to corrosion and deterioration, which damages their main structure. As a result, layers of corrosion products form along the entire surface area, obscuring the object's features (Ghoniem, 2011). Some of these products are stable and they may in fact protect the underlying metal; but others are reactive and may contain chloride salts that induce further corrosion (Gettens, 1970). Such chloride-based compounds may consist of nantokite (CuCl) or paratacamite and its polymorphs, $Cu_2(OH)_3Cl$, which may lead to the pulverization of the metal in a process known as "bronze disease" (Scott, 2000). The patina is usually non-uniform and corrosion characterized by pitting is a common phenomenon (Rahmouni et al., 2009).

Figure 1. Location of Aniba site © Google map

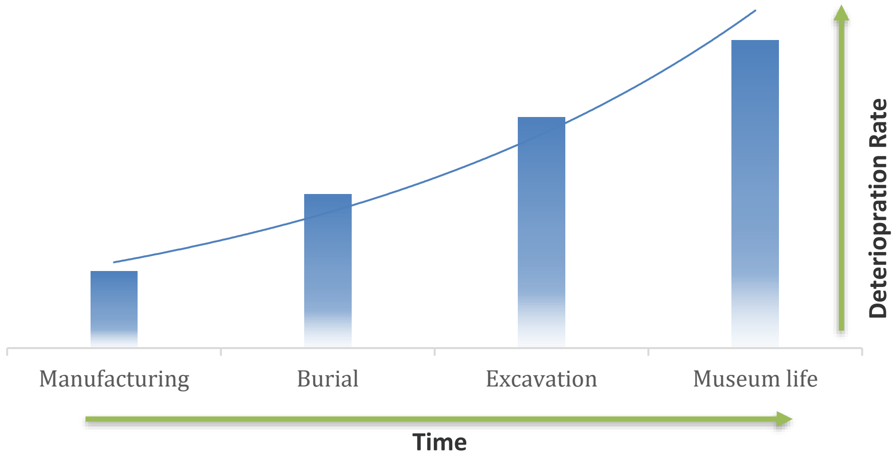

Figure 2. Deterioration of archaeological objects through time and post-excavation

Characterization of archaeological metal artifacts is necessary in order to acquire a better understanding of the preservation condition of ancient objects, corrosion processes, and conservation methods (Doménech etal., 2012; Di Turo et al., 2017).Scanning Electron Microscopy (SEM-EDS), X-ray diffraction (XRD), X-ray fluorescence (XRF), Fourier Transform Infrared Spectroscopy (FTIR), laser inductively coupled plasma (LA-ICP-AES), and other techniques have all been extensively used in the study of ancient metal artifacts. All of these can be classified as non-destructive approaches, with the primary goal of preserving the integrity of cultural objects without damaging its historical or artistic value. It is obvious that research and conservation practice is increasingly turning to the use of such techniques. In this context, a multi-analytical approach has become critical in order to achieve good results, answering to issues concerning the cultural heritage materials (Di Turo et al., 2016; Tissot et al., 2015).

Any cleaning procedures must be carried out with considerable care and attention to the form, function, and material of the original object (Abdel-Kareem et al., 2016). The most significant criterion to consider is that the chosen procedures do not damage the surface of the metal objects and that they are applied properly to avoid any damage due to improper conservation techniques (Novakovic et al., 2013).

The main goal of conservation processes is to improve the object's long-term preservation by making it safe and ready for display. Any conservation activity should be preceded by a comprehensive examination and documentation of the artifact (Abdel-Kareem et al., 2016; Ghoniem, 2011).

2. HISTORICAL BACKGROUND

The first man-made mirrors were typically made of polished stone such as black volcanic glass obsidian and had a round reflective surface; some were conical. These mirror surfaces were slightly convex and highly polished. Their diameters were approximately 9 cm. Some examples of this kind of mirrors were found in Anatolia (modern-day Turkey) by Mellaart in the region of the Neolithic settlement dating to ca. 6200 BC (Enoch, 2006; Vit and Rappenglück, 2016).

Egypt is rightfully considered one of the birth-cradles of mirror-making. While there is no evidence of metallic mirrors from Egypt's Predynastic period, archaeologists have discovered objects in the burials of the so-called Badari culture (5000 – 4500 BCE) that could well be considered the first man-made mirrors. Selenite is the mineral that was used to make a polished disk that was found near Badari village in Southern (Upper) Egypt and is considered to be one of the earliest human mirrors. However, a highly polished selenite flake set into a wooden frame has been dated to the Badarian era (c. 4400 to 4000 BC), indicating remarkable ingenuity in the design of this early prototype. According to several researchers such early mirrors were likely used not only as cosmetic tools, but also as ritual objects, symbolizing the Sun and Ra (and other deities), and they were unlikely used as mirrors in the modern sense (O'Neill, 2011).

Mirrors quickly became quite sophisticated, with a well-rounded disc made of bronze and an elaborate handle. The earlier mirrors were made of copper, and later of the alloys of tin and copper (bronze), and then eventually with some addition of silver and gold (sometimes, although rather rarely, they were entirely made from silver). The earliest copies of Egyptian copper mirrors date from 2900 BCE. The shapes of many of them indicated that they likely had handles, made of wood or ivory (Brunton and Caton-Thompson, 1924).

The studied mirror dates back to the New Kingdom, and it is a development of the mirrors manufactured in ancient Egypt, and this appears through its distinctive shape compared to the typical upside-down pears with handles shape that was characteristic in the Earliest Times through the New Kingdom periods in the history of ancient Egypt. The typical ancient Egyptian mirror was essentially flat (a few were convex or concave), polished on both sides, and slightly elliptical (wider than high) with a sharp metal tang at the bottom that fit into a handle made of wood, stone, ivory, horn, metal, or clay. The highly polished surface was protected with cloth, animal hide, or woven rushes. In the tomb of Tutankhamen, there was a mirror in its own custom-fitted wooden box, embossed with sheet gold and inlaid with colored glass, carnelian, and quartz. But the studied mirror is characterized with handle in the shape of cross-band or tyet sign (lilyquist, 1979; Pendergrast, 2004).

Figure 3. Queen Kawit sitting on a chair, with a servant girl arranging her hair, while she drinks from a bowl. In her left arm she holds a mirror, as if to check her wig. Egyptian Museum, Cairo

Figure 4. Mirror with a handle in the shape of a young woman holding a papyrus umbel. Accession Number: 1972.118.30, Dynasty 18. New Kingdom. © MET Museum

Mirrors often held a cultic role in Egypt and were given as dedications, with their round reflective surfaces thought to represent the sun, and were also dedicated in Greek temples. Throughout their history in Egypt, mirrors were associated with Hathor, and in the Greco-Roman period with Aphrodite (Thomas and Acosta, 2017). The ancient Egyptians, Indians, Chinese, Mayans, Incas, and Aztecs buried their dead with metal or stone reflectors, to hold the soul, ward off evil spirits, or allow the body to check its appearance, before taking the final trip to the afterlife (Anderson, 2007; Pendergrast, 2004).

3. MATERIALS AND METHODS

3.1 Mirror's description

The studied object is a metal mirror (GEM No. 34194, in storage, inorganic lab, Grand Egyptian Museum). It was discovered at the Aniba archaeological site, Lower Nubia, Aswan, Egypt by G. Steindorff in 1931 and is dated to the New Kingdom. The mirror was cast as a single piece, presumably using the lost-wax process. It is slightly oval in shape, with a tang for handle attachment (wooden or metallic). Numerous examples of this type exist in different museums around the world. The mirror was not decorated.

The mirror is in a poor condition. Corrosion products, soil deposits and encrustations cover a large portion of the surface area of the mirror, there are wooden remains/fibers on the obverse side. Corrosion products and encrustations are present and display different colours (white, red-brown, black, greenish blue, light-green, and green) that cover both sides of the mirror, a reversal of normal corrosion layers. The handle of the mirror is missing. The mirror is intact except for a small crack at the edge of the tang (Fig. 5). The physical deterioration and corrosion products of the bronze mirror were documented and mapped using AutoCAD and the corrosion products were identified based on the analysis performed by X-ray diffraction (Fig. 6). This helped in assessing the current condition of the studied object emphasizing areas of weakness and active corrosion that needs immediate treatment. It also helped to distinguish the overlap between the corrosion compounds and deterioration aspects such as (cracks, incrustations, stain). Each aspect and corrosion product were characterized with a specific color or symbol. The diagram legends are included.

Various investigative and analytical methods were carried out on the mirror to characterize and evaluate the conditions of preservation and to identify types of the corrosion products covering this mirror.

Initially the mirror was investigated using stereo microscope in order to evaluate its condition and to understand the nature of surface and corrosion products and subsequent analyses included X-ray radiography, Multispectral Imaging and Reflectance Transformation Imaging, metallographic examination, XRF and XRD.

Figure 5. The mirror stored at the Grand Egyptian Museum

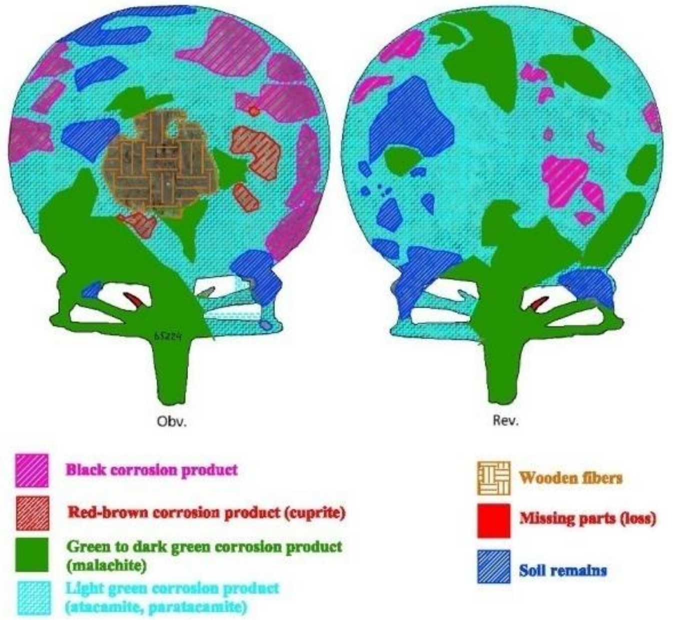

Figure 6. Documentation of the deterioration aspects and corrosion products of the bronze mirror using AutoCAD program

3.2 X-ray radiography

The mirror was examined with portable X-ray radiography (Radioflex RF-200SPS) to examine the surface morphology, and to understand the casting features. Radiographed image was captured at 80 kV, 2 mA, and 6 second exposure.

3.3 Multispectral Imaging and Reflectance Transformation Imaging (RTI)

One of the techniques used for documenting and studying the mirror was reflectance transformation imaging (RTI), which creates an interactive image by varying the angle of illumination. The mirror was photographed using RTI to observe and record the details on the surface of the mirror and retrieve information about the material and methods of manufacture using Canon eos kiss, Lens 18:55mm, Shutter speed: 160, f-stop 10, Iso 10. (Manfredi, 2013; Florindi et al., 2020; Ciortan, 2016; Leach, 2021). The mirror was also photographed using multispectral imaging (visible-induced infrared luminescence, ultraviolet visible fluorescence) was used in order to identify if it had been previously treated or has ancient pigments. The corrosion layers and the surface of the mirror were further investigated using a computational post-processing technique of D-Stretch.

3.4 Metallographic examination

The macroscopic observations of the mirror were performed in order to evaluate its conservation status and production techniques. A tiny sample was taken for cross-section. The sample was analysed using p-XRF. It was mounted in a mold using EpoxiCure TM 2 (resin 5+ hardener 1) and the mold was left about 24 hours to harden. Sand paper of different grit sizes was used to polish the samples starting with p120, p300, p400 and finishing with p2000 grit. The sample was further wheel polished with oil, using a 1-micron abrasive and polishing cloth followed by 0.05 micron. The sample was examined using a polarized light microscope with (Nikon MICROPHOT) (Scott, 2014; Macleod, 1981; Scott, 2002).

3.5 Potable X-ray Fluorescence (p-XRF)

In order to identify the elemental composition of the alloy, a specific area of the mirror's surface was cleaned and analyzed using a handheld Bruker Tracer Spectrometer (40 kV high voltage, 20 A anode current) for 40 seconds live time irradiation at the GEM-CC as a non-invasive method.

3.6 X-ray diffraction (XRD)

A sample of the corrosion products was examined with X-ray diffraction at GEM-CC to better understand the components of the corrosion layers and their nature. The corrosion sample was grinded using an agate mortar for obtaining 5–10-micron grain size. The X-ray diffractometer system (PANalytical, X’Pert Pro, PW 3040/60 model) was used, with a Cu anode, working at 30 mA/40 kV at a 25 °C with a step size (2θ) of 0.033. An X-ray tube produced a monochromatic Cu Kα radiation of wave length 0.154 nm, recorded from (2θ) 5° to 70° in the case. Samples were grinded using an agate mortar for obtaining 5–10-micron grain size. X’Pert high score data acquisition and an interpretation software (Malvern PANalytical, Malvern, UK) were used for interpreting the results.

4. CONSERVATION AND PRESERVATION PROCESSES

4.1 *Active corrosion test*

Before treatment, the active corrosion was analyzed using the silver nitrate chloride spot test. Minute samples were collected from areas of bright green, powdery corrosion. The samples were placed on a glass slide, onto which one drop of 2.5% nitric acid (in deionized water) was added, followed by one drop of 3% silver nitrate (in deionized water). The development of a white precipitate indicates the presence of chlorides, and therefore active bronze disease (Laver, 1978; Riss, 1993; Scott, 1990).

4.2 *Temporary consolidation*

Before treatment and the removal of corrosion products from the mirror's surfaces, both sides of the mirror were first supported with thin strips of Japanese tissue attached with 0.5% of Klucel-G (hydroxypropyl cellulose) in ethanol by brushing to protect the mirror from any further deterioration caused during the pressure of the mechanical cleaning process (Fig.7). The weak parts were consolidated with paraloid B-72 3% in acetone by brushing (Feller and Wilt, 1990).

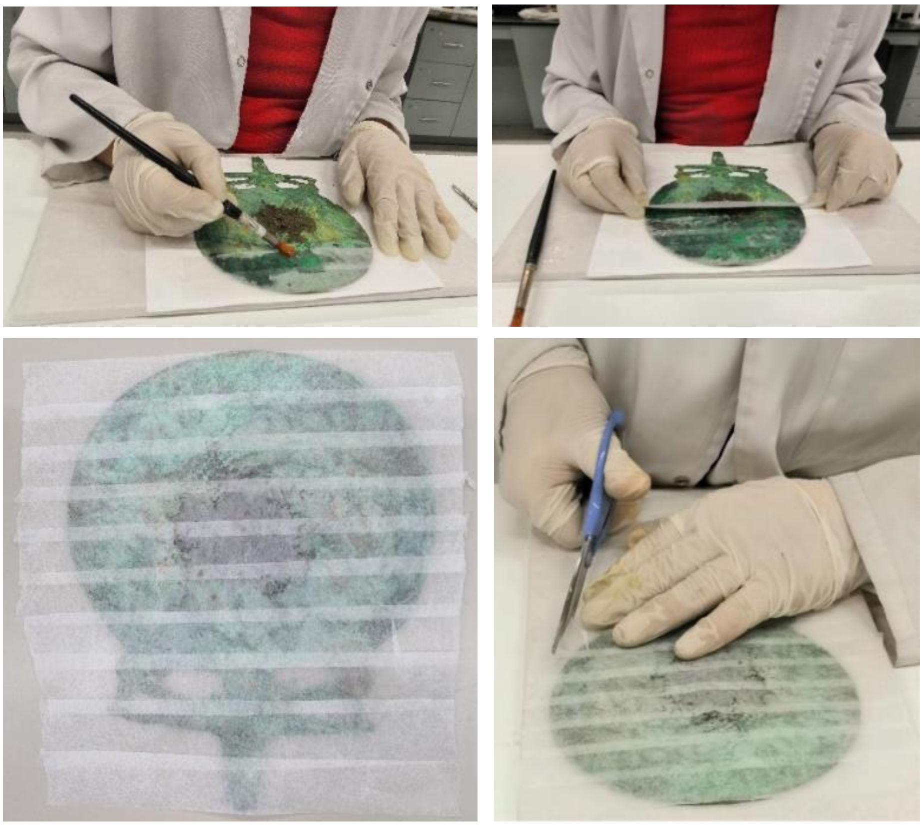

Figure 7. Appling a facing layer using tissue Japanese paper with 0.5% of Klucel-G in alcohol as a temporary consolidation/support of the bronze mirror.

4.3 *Surface Cleaning*

Based on the condition of the bronze mirror, the mechanical method was chosen for the cleaning procedure to remove any incrustations and corrosion products. All mechanical cleaning was carried out in accordance with conservation guidelines (Koh, 2006).

4.4 *Coating and stabilization*

It was necessary to apply a corrosion inhibitor in addition to a protective layer of coating material due to the mirror's poor preservation condition and the presence of active corrosion.

5. RESULTS AND DISCUSSION

5.1 *Characterization and the condition of the mirror*

Visual observation and microscopic examination revealed that the mirror is covered with a thick layer of encrustations, and corrosion products that obscure any decorations that might be on the surface of the mirror. The texture and surface morphology of the corroded layer of encrustations is variable: in some parts it is compact, while it is loose and less thick, in others. The surface is covered with soil residues, interspersed with corrosion products. The mirror's surface is distinguished by a rough, corrosive surface, and pits with a various types of corrosion products in different colors: dark green, light green, greenish blue, and white-gray surfaces covered with soil residues. Additionally, there are some areas where active corrosion is present, providing further proof of the corrosion process's ongoing progression (Fig. 8) (Pollard et al. 1989; De Ryck, 2004).

5.2 Stereo Microscope

Through the stereo microscope it was possible to discern the different patina layers and areas where original surface remains. Photo micrographs point to different colours of corrosion products on different parts of the surface of the mirror in addition to deposited soil remains (Weichert, 2004). Observed the presence of a red/pink microconstituent of unalloyed copper, that present in round shape filling previous empty spaces as pores among the intergranular corrosion alternating its presence with cuprite. Generally referred as redeposited copper, its mechanism of formation has taken various interpretations regarding its shape/morphologie, proximity to other metallic phases, as eutectoid, or even proximity to Cu-S inclusions. Red stain might be a secondary deposition of cuprite, it could be close to an iron object or iron component from the soil but unfortunately, we weren't analysis it (de Figueiredo, 2010; Tronner, 1995).

Wood fragments coherent to the metal surface. These fragments could be that the mirror was in its own custom-fitted wooden box. The mirror in this study presents an interesting case of wood fragments that presumably had cohered to the metal surface during the centuries of its burial. There is insufficient information on the context and conditions in which the mirror had been found, but by investigating the wood and metal surfaces, it seems that the mirror had been placed on a wooden plank during it's burial. Whether or not the plank formed the base of a box is debatable, yet in the case of the funerary furniture of King Tut Ankh Amun, his mirror had been placed in its custom-fit box. By comparing the corrosion products on both sides of the mirror, it is clear that the side adjacent to the wood is more corroded than the opposite side. An explanation of this phenomenon may be due to the volatile organic compounds (VOCs) such as formic and acetic acid that are emitted from wood in small quantities when exposed to certain conditions such as heat and humidity. When wood is in direct contact with metals, the emitted gases are one of the causes of metal corrosion (Figure 9) (Elmarazky and Kamal, 2021).

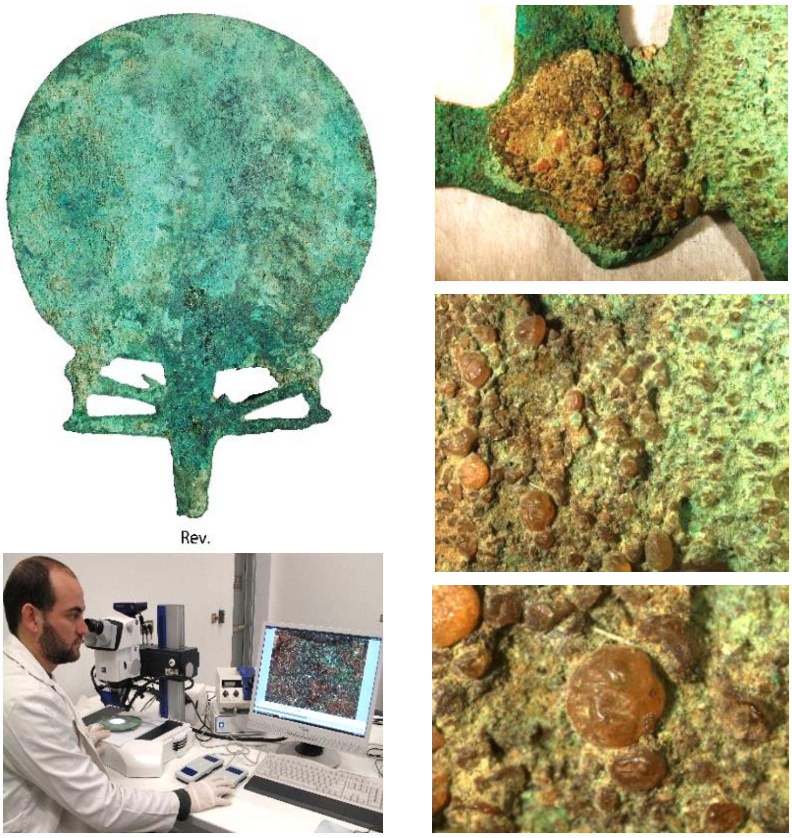

Figure 8. Encrustation under higher magnification showed quartz crystals, and different soil deposit as confirmed by XRD. Light green powdery corrosion an indication to active corrosion (atacamite) as confirmed by XRD. (reverse)

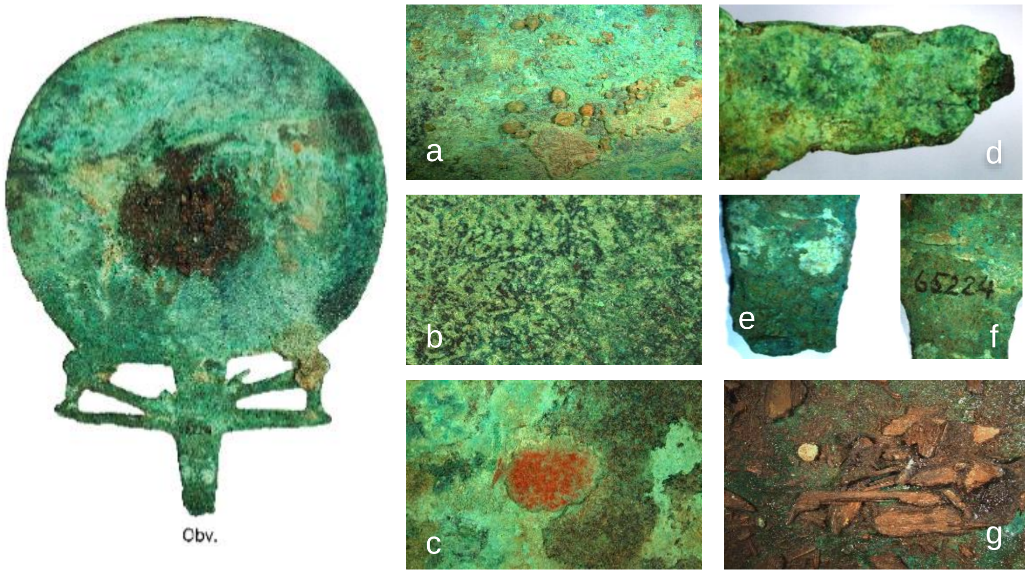

Figure 9. Images show different types of corrosion apparent at the surface. (a) powdery corrosion, soil deposits, and area of flaking. (b) The corrosion either grew in spots or sometimes covered wider areas of the object. The colors ranged from black to various shades of green. Needle-like structures were observed. (c) Observed the presence of a red/pink microconstituent of unalloyed copper, that present in round shape filling previous empty spaces as pores among the intergranular corrosion alternating its presence with cuprite. Generally referred as redeposited copper. (d) tang of the mirror corroded, (e) have areas with active corrosion, (f) ID written directly on the tang's surface, (g) wood fragments coherent to the metal surface.

5.3 X-ray radiography

Radiographs showed that structurally the mirror is in a good condition and confirmed that it was solid cast. The casting has a fine, overall porosity and is relatively free of casting defects, holes, and patches. Radiography additionally suggested that the mirror may possibly have lead segregation (scattered white inclusions may indicate lead segregation) (Fig. 10).

5.4 Multispectral Imaging and Reflectance Transformation Imaging (RTI)

The application of RTI imaging on the bronze mirror yielded significant results about the depth, profile, and the direction of the engraving. It was also helpful to evaluate the efficacy of the mechanical cleaning by using images of different angles, after analysis of the data with the use of the respective RTI software (Fig. 11). Visible induced luminescence imaging did not indicate any previous treatment, or the presence of pigments remains on the surface of the mirror. A computational post-processing technique of D-Stretch was very effective in enhancing the corrosion layers revealing the corrosion products (Le Quellec et al., 2015) (Fig. 12).

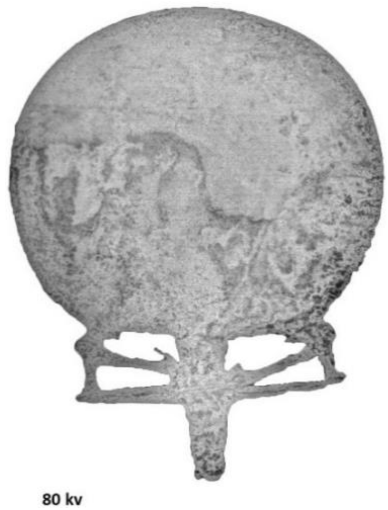

Figure 10. Radiography of mirror, revealing only minor casting defects, holes, patches, and possible lead segregation.

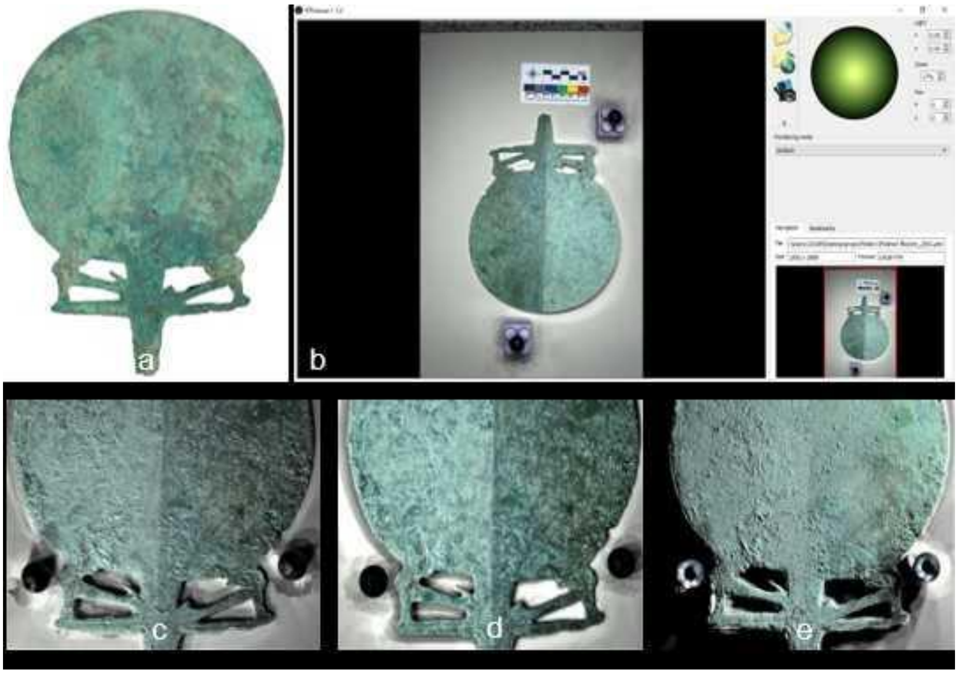

Figure 11. a-Up left: Digital image of the bronze mirror. B-Up right: RTI viewer software. Lower three images c,d,e: RTI visualizations of the bronze mirror helped with surface clarity and cleaning process assessment by visualizations of the mirror's surface both before (d-half-right) and after cleaning (d-half left).

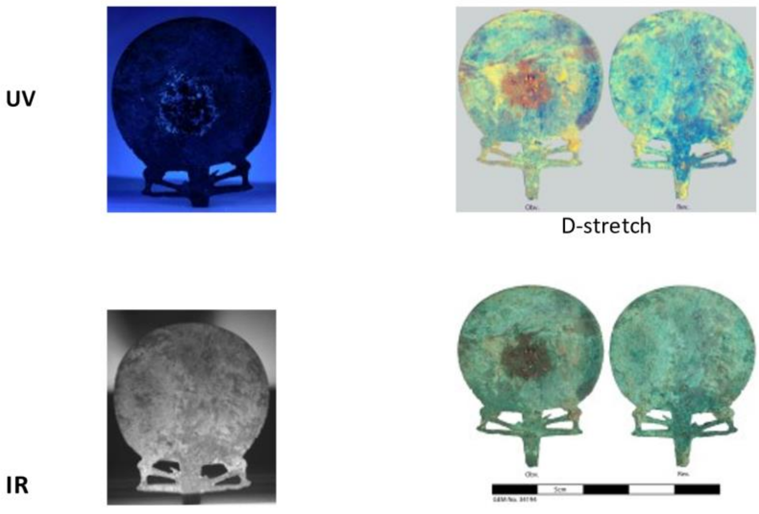

Figure 12. Detail of multispectral imaging. ultraviolet visible fluorescence (UVF) and D-Stretch with enhanced of the corrosion layers (far right) and, visible-induced infrared luminescence.

5.5 Metallographic examination and XRF results

The results of metallographic examination of the mirror sample showed that the morphological structure of the mirror alloy is characterized with hard crust and corrosion layers, which was due to the corrosion formed on its surface (Figure 13). The corrosion products formed an inhomogeneous layer on the surface (Fig. 14). The results revealed that the formation of corrosion layers are those that are typical for an ancient bronze with layers of CuO and $Cu_2CO_3(OH)_2$. There are also areas of redeposited copper where it has been converted from cuprite to copper. The XRF results using Thermo Scientific Niton XL3t GOLDD+ XRF Analyzer. Ag anode (6-50 kV, 0-200 µA max). Geometrically Optimized Large Area Drift Detector (GOLDD) Proprietary detector with 180,000 throughput cps Resolution: < 185 eV @ 60,000 cps @ 4µ sec shaping time. Alloy Modes: Metal Alloy, Electronics Alloy, Precious Metals indicate that the mirror sample is composed of a tin bronze alloy. Copper is the main element, with a good amount of tin and variable traces of lead and iron are detected in spectra (Table 1). The alloy is tin bronze alloy and consistent with several authentic example of ancient mirror bronzes. The alloy is tin bronze alloy and consistent with several authentic example of ancient mirror bronzes. Tin is the primary alloying element used to produce bronze, and its presence causes the mechanical characteristics of bronze to increase even does not exceed the 7 wt. %, as indicated by the results in Table 1. In antiquity, Lead was a common addition to bronze to produce objects with poor mechanical characteristics to be utilized at room temperature. Although a loss of mechanical properties could be induced, adding up to 2 wt. % of lead does improve the fluidity of the melted bronze alloy. However, if the lead amount is increased to 3–4 weight percent, hardness and toughness are subsequently reduced (Thomas, 2022).

Table 1. Elemental composition of sample using pXRF

Elemental	Cu	Sn	Pb	Sb	Fe
Percentage (Wt.%)	89.7	6.34	1.3	0.8	0.5

Figure 13. Location of XRF sample

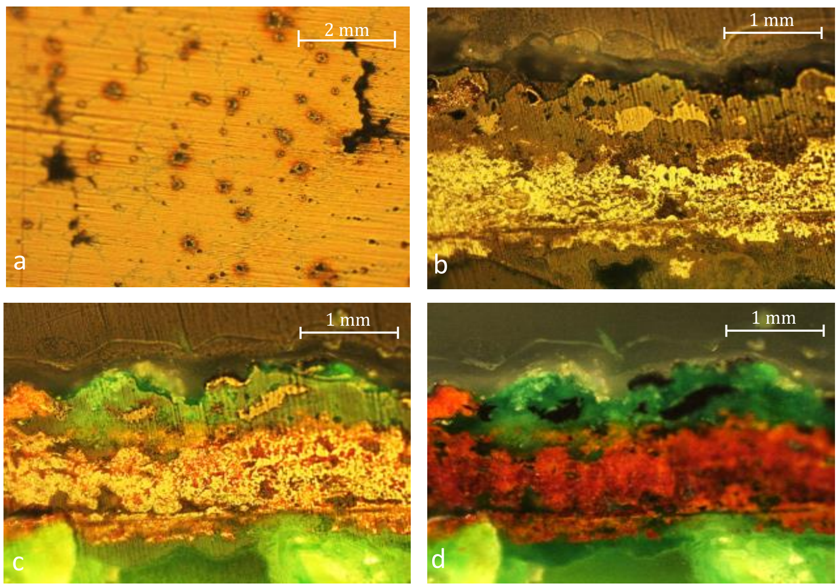

Figure 14. Optical photomicrograph of bronze sample microstructure, (a) showing intergranular corrosion. (b, c) areas of layer corrosion products penetrating beneath the original surface. (d) Cupric oxide (brick red) and copper carbonates, malachite (dark green) and cuprous chloride (light green) corrosion products are evident.

5.6 X-ray diffraction (XRD)

Using XRD, the nature of corrosion products was investigated, and the results gave valuable insight into the corrosion layers. The use of XRD has revealed the presence of quartz (SiO2), as well as copper species such cuprite (Cu_2O), carbonates like malachite ($Cu_2(OH)_2CO_3$), and atacamite (Cu2$(OH)_3$Cl) (Table 2). This information provides evidence that the outermost corrosion layers are formed also via the interaction between soil constituents (Cl, Si, Ca, and CO_2) and metal corrosion products, primarily constituted of copper, whose amount on the artefact surface is often decreased by the long-term corrosion. Carbonates, chlorides, and silicates are signs of a strict interaction between soil constituents and object corrosion products (Ingo et al. 2006).

Table 2. Corrosion products analysed using XRD

Sample	Corrosion product	Chemical name	Chemical formula	Density g/cm^3	Card No.	Percent. %
copper corrosion products	Cuprite	copper (I) oxide	Cu_2O	6.1	02-0635	16
	Malachite	copper carbonate hydroxide	$Cu_2(CO_3)(OH)_2$	3.8	02-0981	24.9
	Quartz	silicon dioxide	SiO_2	2.65	02-0657	17
	Atacamite	Copper (II) chloride hydroxide	$Cu_2Cl(OH)_3$	3.76	05-0098	26.6
	Paratacamite	Atacamite group	$Cu_3 (OH)_6Cl_2$	3.74	05-0132	13.5

6. CONSERVATION PROCESSES

6.1 Temporary preservation

Due to the lengthy duration of the study and conservation process (several months), it was necessary to carry out a temporary preservation process for the mirror to continue the conservation process optimally. Temporary preservation of the bronze mirror was performed using a sealed container of acid-free plastic to isolate it from the surrounding environment (Fig. 15). Silica gel (100 g, transparent balls, pores diam. 4.5-7.0 nm nbsp) was placed inside the plastic container (designed for mirror preservation) to stabilize the relative humidity at less than 35%.

Figure 15. Object temporary rehousing during conservation processes in acid-free box with blue silica gel as a desiccant

6.2 Cleaning process

Analyses has been useful in revealing minute features of the mirror's surface (such as shape and cracks ... etc.), elemental composition, and preservation condition.

XRF revealed the elemental composition of the mirror, which helped in understanding its alloy, as well as assists in making good decisions regarding conservation plan and long-term care.

The corrosion products were identified using the XRD technique, along with their nature—whether they were stable or active—and whether or not they should be subjected to proper conservation methods. Also, the examinations and analyses performed on the mirror aided in deciding whether or not to clean it. The metallographic images made it easier to comprehend and track the layers of corrosion and their sequence, which in turn contributed in performing effective cleaning procedures without harming the original surface of the mirror, which must be preserved (Ingo et al. 2006).

The mechanical cleaning was done with care to avoid damaging the original surface of the mirror. The corrosion products on the surfaces of the mirror were removed mechanically using toothbrushes, scalpels, and micromotor (inGco). After removing the corrosion products from the surface of the mirror, treatment involved the mechanical removal of the copper chlorides using a needle and a scalpel until bare metal was exposed. The excavated zone was then coated with a paste of silver oxide powder dissolved in ethanol, to fill the pits and arrest the active corrosion. After mechanical cleaning and through visual observation, the surface morphology of the studied mirror started to appear, and engravings on the edges of the mirror became legible. These designs were perhaps added to the mirror after casting using a pointed tool and small blows from a hammer. As a result, the mechanical cleaning was quite successful and achieved positive results. At this point, the decision was taken not to perform any other cleaning procedures: the mechanical cleaning process was sufficient to achieve the desired results while preserving the original surface of the bronze mirror (Figs. 16, 17).

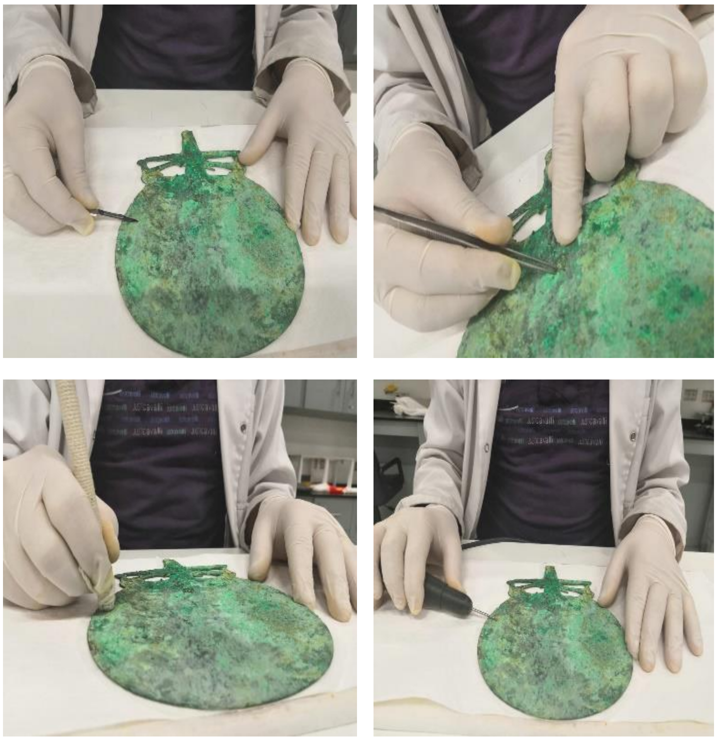

Figure 16. Mechanical cleaning processes of the bronze mirror using different tools

Figure 17. The bronze mirror during (left), and after (middle & right) conservation and removal of the corrosion products

6.3 Stabilization and coating

Both surfaces of the mirror were carefully cleaned using alcohol to get rid of dirt or dust before applying the corrosion inhibitor with nano-reinforcement materials on the surfaces of the mirror. According to the results of the experimental study conducted by El-shahawi et al, 2022, which confirmed that the Jatropha extract was very effective and suitable inhibitor for protecting bronze coupons against corrosion, three layers of Jatropha extract "two hours interval between each application " at 30ppm in alcohol with Nano silver were applied to the mirror surfaces by brushing to prevent further corrosion and any future deterioration. Finally, a protective coating of paraloid B-72 3% in acetone was applied to the mirror to protect it from environmental condition while in storage at the museum.

6.4 Rehousing and ideal storing condition for storing process

A new acid-free box was created to preserve the mirror. The box has a lid with a transparent cover (Fig. 18). In uncontrolled storage conditions, metal artifacts and its alloys can readily fall prey to bronze disease. After conservation, therefore, it was necessary to store the bronze mirror safely in order to prevent further damage. A major concern of museums is to maintain proper environmental conditions for the collections (Rimmer et al., 2013). Accordingly, the mirror has now been stored in an ideal climate-controlled condition that does not expose it to corrosion, using the following storage parameters:

- the mirror was stored in an airtight acid-free box with lid;
- the relative humidity was fixed at less than 35% using silica gel as a dehumidifier material (fluctuations in humidity can cause a lot of damage) ((NPS museum, Handbook, Part 1, 2001);
- the temperature was set at 18-22 °C;
- a data logger was installed inside the mirror's box to track changes in storage conditions;
- storage of the mirror supported to minimize handling and damage (Muros, 2011).

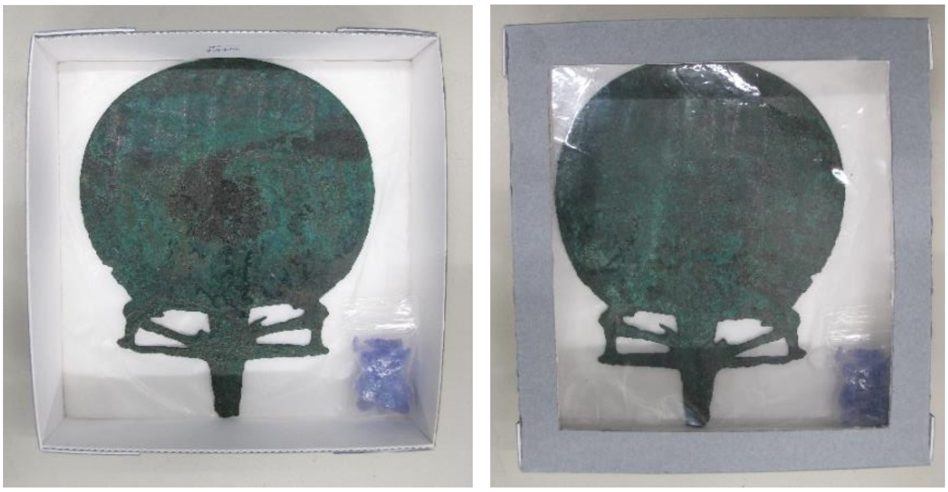

Figure 18. Object rehousing process in a new box

7. CONCLUSION

The studied mirror from Aniba site was in a poor condition requiring the removal of corrosion layers and encrustations on the mirror's surface. They were successfully removed via mechanical cleaning, revealing the mirror's original surface and border designs. Based on the results of an investigation and analysis, the mirror is composed of bronze alloy. A corrosion inhibitor containing 30ppm jatropha extract in alcohol combined with 10ppm nano silver composites was brushed over the mirror's surface to protect it from corrosion and future deterioration processes. Finally, a protective coating of paraloid B-72 3% in acetone was applied as an extra layer of protection.

AUTHOR CONTRIBUTION

Conceptualization, M.R., A.E. and Z.A.; methodology, M.R., A.E. and Z.A.; validation, M.R. and Z.A.; formal analysis, M.R., A.E. and Z.A.; investigation, A.E.; resources, A.E.; data curation, A.E.; writing—original draft preparation, A.E.; writing—review and editing, M.R., A.E. and Z.A.; visualization, A.E.; supervision, M.R. and Z.A. All authors have read and agreed to the published version of the manuscript.

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