



Susanne Gänsicke & Stefan Hagel (eds.)

MUSIC *from*
ANCIENT MEROË

Reconstructing
Queen Amanishakheto's Auloi

MFA/Boston

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RECONSTRUCTING QUEEN AMANISHAKHETO'S AUROI

edited by

Susanne Gänsicke and Stefan Hagel



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RECONSTRUCTING QUEEN AMANISHAKHETO'S AULOI

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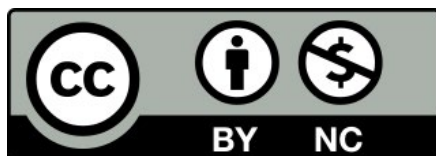
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Foreword

Lawrence Berman

“The auloi of Meroë.” So read the label on a gray archival box housed with our excavation records. What were the auloi of Meroë? I must confess, when I first arrived at the MFA in 1999, I had no idea. The name was so evocative, mysterious, romantic even. I soon found out that the auloi were remnants of musical instruments—double reed pipes, played in pairs—discovered in an ancient Nubian queen’s tomb in northern Sudan. Inside the gray box were not the auloi, of course, but a jumble of notes and papers relating to this important find, the single largest collection of such instruments ever discovered, “The Auloi of Meroë” being the title of a 1946 article by Nicholas Bodley on this important find. I also learned that their reconstruction posed a formidable challenge as they had been reduced to little more than fragments.

Darcy Kuronen, Matthew Siegal, and Rita Freed deserve all the credit for raising funds from the Visiting Committees of their respective departments to jumpstart the conservation project and the work of an international team of scholars beginning in 2013 to research and, so far as possible, reconstruct these precious instruments.

After May 2015, once or twice a year the team from Europe would come to Boston to work on the fragments. The scholars would camp out in our library; we could not use the room for any other purpose while the fragments were spread out on the big table. The pieces were kept in archival boxes that took up several shelves in our office safe. Every morning we would take the boxes out of the safe and every evening we would put them back again. I had the pleasure of seeing the number of fragments dwindle year by year as the instruments took shape before our eyes. It was the most extraordinary process of painstaking study, coordination, and reconstruction I have ever witnessed.

It was some time before the researchers were certain just how many instruments we had. Now we know: twelve pipes making six auloi, now beautifully housed. A magnificent achievement! We are very proud to present the results of our years-long collaboration to a wide audience of musicologists, archaeologists, historians, conservators, curators, and the public everywhere.

Lawrence M. Berman

John F. Cogan, Jr., and Mary L. Cornille Chair, Art of Ancient Egypt,
Nubia, and the Near East, Museum of Fine Arts, Boston

Perspectives

What were those strange bits of corroded metal in the basement of the Egyptian storerooms of the MFA? I remember asking Curator Emeritus Dows Dunham that during a summer internship with him following my first year of college. He shrugged and said sorrowfully, “They are auloi, important reed instruments found at Meroë, but unfortunately they are in such bad condition, little can be done with them.”

Fast forward decades, when Darcy Kuronen, then Chair of Musical Instruments at the MFA, approached me in my position as Chair of Ancient Egyptian, Nubian, and Near Eastern Art and asked if I would be interested in partnering in a joint effort to restore the auloi. Darcy had not only found funding, but also the ideal team to restore, study, and replicate them. What an opportunity!

Year followed year, as the dream team of a conservator and three music archaeologists with backgrounds in ancient studies, musicology, and engineering came together in Boston and slowly the auloi took shape. It is fair to say their results exceeded all our expectations.

As the sounds of the auloi come alive again, I rejoice in knowing how pleased it would have made Mr. Dunham.

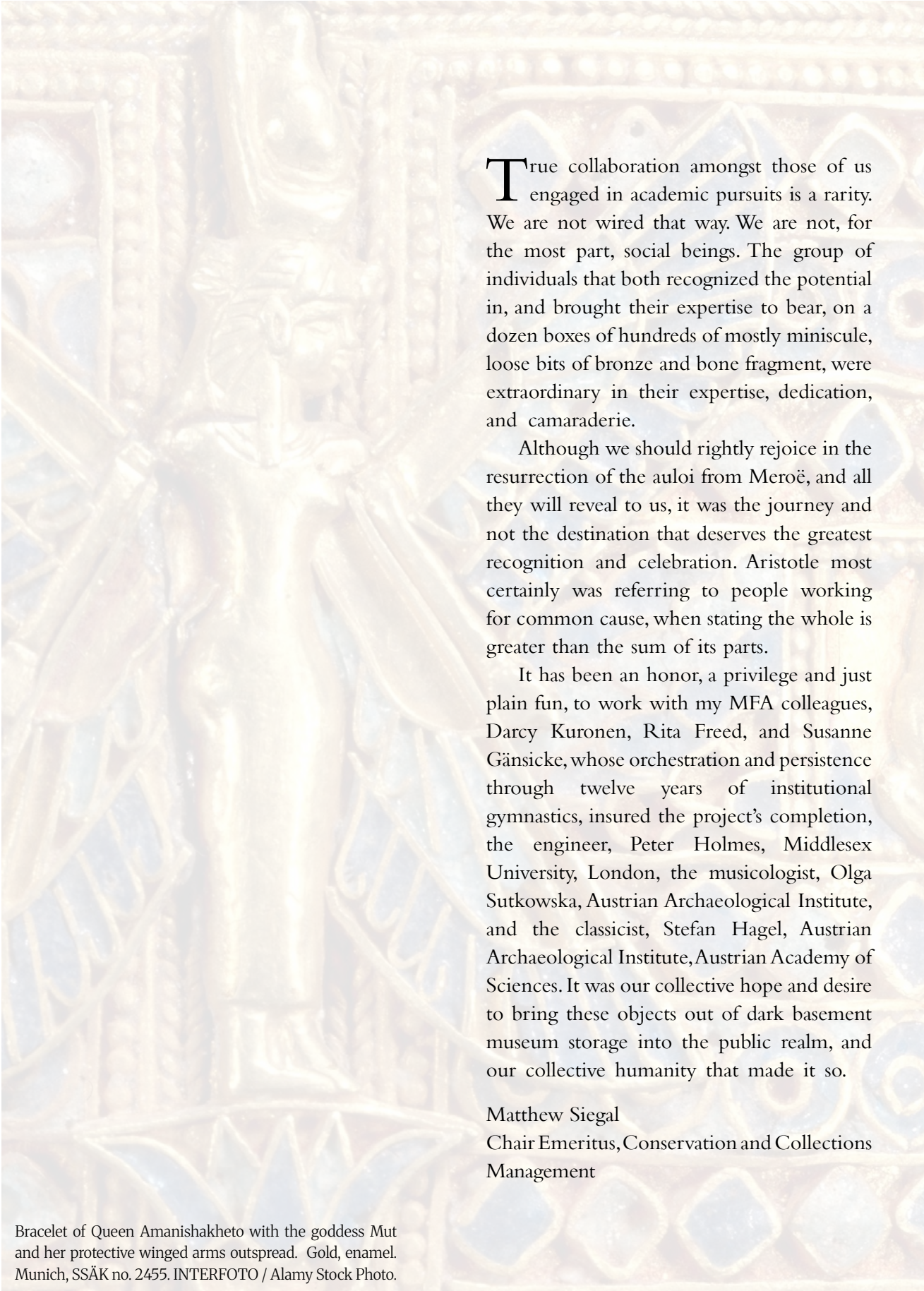
Rita Freed

Chair Emerita, Department of Ancient Egyptian, Nubian and Near Eastern Art

The Museum of Fine Arts, Boston, is home to an outstanding collection of over 1,200 musical instruments from all over the world, dating from antiquity to the present, and I was honored to curate that collection for nearly thirty-four years. Many in the field of instrument study, however, are unaware that what are arguably the rarest and most significant instruments at the MFA are cared for by the Department of Egyptian and Ancient Near Eastern Art, namely the auloi forming the basis of this book. I myself was unaware of these amazing instruments when I began working at the Museum in 1986, and I must thank my late colleague Gary M. Stewart for noticing some fragments from this cache on display just a few years later. Inquiring about the instruments with Dr. Timothy Kendall, an Egyptologist who was then an associate curator on the MFA’s staff, Stewart was told that there were several boxes of further fragments in storage. From then on it was clear to me that something must eventually be done to fully explore this extremely rare musical find. The rest of that story is presented elsewhere in these pages, but I am extremely gratified that the Museum’s auloi have finally become the source of serious scholarly study, of which this important book is just one manifestation.

Darcy Kuronen

Former Pappalardo Curator of Musical Instruments



True collaboration amongst those of us engaged in academic pursuits is a rarity. We are not wired that way. We are not, for the most part, social beings. The group of individuals that both recognized the potential in, and brought their expertise to bear, on a dozen boxes of hundreds of mostly miniscule, loose bits of bronze and bone fragment, were extraordinary in their expertise, dedication, and camaraderie.

Although we should rightly rejoice in the resurrection of the auloi from Meroë, and all they will reveal to us, it was the journey and not the destination that deserves the greatest recognition and celebration. Aristotle most certainly was referring to people working for common cause, when stating the whole is greater than the sum of its parts.

It has been an honor, a privilege and just plain fun, to work with my MFA colleagues, Darcy Kuronen, Rita Freed, and Susanne Gänsicke, whose orchestration and persistence through twelve years of institutional gymnastics, insured the project's completion, the engineer, Peter Holmes, Middlesex University, London, the musicologist, Olga Sutkowska, Austrian Archaeological Institute, and the classicist, Stefan Hagel, Austrian Archaeological Institute, Austrian Academy of Sciences. It was our collective hope and desire to bring these objects out of dark basement museum storage into the public realm, and our collective humanity that made it so.

Matthew Siegal
Chair Emeritus, Conservation and Collections
Management

Bracelet of Queen Amanishakheto with the goddess Mut and her protective winged arms outspread. Gold, enamel. Munich, SSÄK no. 2455. INTERFOTO / Alamy Stock Photo.

Preface and Acknowledgments

Susanne Gänsicke and Stefan Hagel

This book presents the publication of our recent research and conservation project on the Auloi of Meroë. The cache of ancient wind instruments was excavated in 1921 in the tomb of Queen Amanishakheto at Meroë in the northern Sudan by the Harvard University-Museum of Fine Arts Expedition. Although recognized as important at the moment of discovery, the instruments were highly deteriorated and fragmented due to their thin-walled nature, potential intentional damage inflicted during interment, and two thousand years of burial in the desert sand. Over decades, scholars had attempted to understand the find, but the sheer number of fragments had made a meaningful interpretation almost hopeless. Incompletely published, this largest instrument find of the western ancient world had thus remained a mystery treasure, and a distant dream of possible music-archaeological achievement.

In 2013, finally, special funding at the Museum of Fine Arts, Boston allowed a multidisciplinary team of conservator, scientists, and music archaeologists, to start a collaboration that has now entered its twelfth year, piecing together material evidence and reconstructing various types of reed aerophones physically and theoretically. Computer simulation and ultimately experimental models made it feasible to explore their musical potential.

With this volume, we present a contextualized narrative of discovery, detailed documentation of the cache as we have analyzed it, and the technical and musical interpretations of these pipes. The complex nature of the material and its degradation necessarily impose limitations, and there remain gaps in our understanding; also, not all elements have survived. We hope this volume will serve readers with various interests, ranging from Nubia and the ancient Nile valley through the histories of music and technology, and particularly the community of scholars and practitioners of the aulos, and will provide information and resources that may stimulate further research.

The first year of the project was funded by donations of the Visiting Committee of Musical Instruments. The following years were supported jointly by the three Visiting Committees of the above-mentioned departments. From 2018 on, our research was mostly funded by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 787522), with the kind support of the J. Paul Getty Museum. It goes without saying that the views presented here reflect only those of the authors; none of the funding bodies is responsible for any use that may be made of the information contained in this volume.

This work required a large team and we wish to express our sincere thanks not only to all authors but to the many individuals and institutions who assisted us with access to the material, analysis, documentation, insights, photography, reconstruction, and support: Damon Beale, Brenda Breed, Timothy Chung, Michele Derrick, Bobby Giglio, Rajiv Gupta, Pamela Hatchfield, Peter Holmes, Christine Kondoleon, Abigail Hykin, Jayme Kurland, Stacey Leonard, Meredith Montague, the Rafter Radiocarbon Laboratory, Deborah Schorsch, David A. Scott, Michael Suing, MeiAn Tsu, Frank Willer, John Woolf, Kamila Wyslucha, and Michael Zach. Billie Jean Collins, finally, expertly and patiently shaped our manuscripts and innumerable images into this book.

1 Ancient Doublepipes

Stefan Hagel

1.1. An Instrument of Its Own Kind

Musical instruments familiar to us, if they are designed to produce diverse notes at all, mostly come in two general categories. Some play only a single pitch at a time and are therefore purely melodic. The typical examples are wind instruments such as flutes, horns, oboes, and clarinets, but also the human voice. Others can produce “harmony” by making several, sometimes numerous, pitches available simultaneously. These include keyboard instruments such as pianos and organs, but also harps, xylophones and their kin, and, with various degrees of restriction, the family of lutes and violins. Western music from at least the middle ages onward typically demands at least three simultaneous notes for fully fledged harmonic progressions.

Ancient West Asian, Mediterranean, and North African antiquity, from the cuneiform cultures of Mesopotamia through Egypt and the Greek and Roman worlds,¹ apparently harbored a very different idea of “harmony,” one of only two different notes heard at the same time. A handful of cuneiform texts transmit terms for such note pairs,² and later the Greeks coined abstract names for consonant pitch relations that we still use in translation: octave, fifth, fourth. But the most important witness to this musical paradigm is a type of wind instrument that dominated music cultures across an area larger than the empires of Alexander and Rome combined: the doublepipe, called *aulos* by the Greeks and *tibia* by the Romans, the plurals being *auloi* and *tibiae*.³ It appears in texts as well as innumerable depictions, on vases, paintings, and mosaics, and also in the hands of statues.⁴ Coming in many sizes, diverse materials, and for various purposes, an aulos consisted of two independent pipes that were played at the same time, one in each hand. The tubes were straight, with the possible exception of a curved horn at the end—a feature that was particularly associated with the Phrygian cult of the Great Mother. Unlike Egyptian and Mesopotamian specimens, Greek, Etruscan, and Roman doublepipes developed a decorative bulb at their upper end, close to the mouthpiece, and sometimes a small flare at the exit. All this did however not affect the internal bore, which was cylindrical.

Translations of ancient works traditionally render the terms *aulos* and *tibia* as “flutes.” While this might have been acceptable some centuries ago, when the English word “flute” could be used in a much more general sense of “woodwind,” it is horribly misleading nowadays, as the sound of the aulos was very different from the soothing timbre we have come to associate with flutes. Auloi were actually reed instruments, excitingly rich in overtones. The oscillation of the air inside the tubes was generated by a mouthpiece made of cane, which wore out and had to be replaced regularly. Although “single reeds” of the clarinet type doubtless existed, the instruments that are shown in depictions and discussed in the texts were almost exclusively equipped with “double reeds,” where one end of the cane was thinned down and flattened to a pair of flexible blades, not entirely unlike the mouthpieces of a modern bassoon or oboe.⁵ Blowing into the gap between the blades set them in vibration, while the length of the tube down to the first open tonehole determined the rate of vibration, which defines the pitch. Unlike the simple form of

1. For venues of musical exchange in the region, see, e.g., Franklin 2015.

2. See, e.g., Shehata and Hagel 2012.

3. For a general introduction with a focus on the Greek world, see West 1992: 81–107.

4. Aulos representations in the Museum of Fine Arts, Boston have been collected by Jayme Kurland Moran: <https://collections.mfa.org/collections/64715/auloi-iconography>.

5. Wyslucha and Hagel 2023.

single reeds known in ancient times, double reeds could be controlled by the lips for greater expression and more precise intonation.

For the tubes, a variety of materials were used: cane stalks with their natural cavities, drilled wood, carefully manufactured sections of hollow bones from animal legs, metal, or a combination of several of these. Among metals, bronze appears to have been used most commonly, but more expensive materials display the status of certain instruments—compare already the oldest extant example, a pair of thin silver pipes from Ur in Mesopotamia.⁶

As manifold as their make were the cultural functions of aulos music (see fig. 1.1). On the one hand, it was the instrument of Dionysian practices, which included not only communal drinking and ecstatic rites, but also the production of drama, where the instrument accompanied both the chorus and the singing “actors.” But the aulos also contributed the primary soundscape to many kinds of sacrifice, it lent its emotions to weddings no less than funerals, it set the rhythm for rowers as well as athletic training and sometimes a marching army, it facilitated physical work, and remained the prime instrument for dancing throughout classical antiquity. Aulos players (“auletes”) most typically performed solo or accompanied singers, but also took part in ensembles with other auloi, strings, and even trumpets.⁷ In the various societal forms of antiquity, the doublepipe may have been played by people from all social strata: slaves and prostitutes, free citizens up to the elite of priests and even kings, such as the Hellenistic pharaoh Ptolemy “the Aulete,” and emperors, like Nero. In Greece, and later all over the Roman empire, star performers could gain international reputation and considerable wealth by winning musical competitions organized by various cities, most famously the Pythian Games at Delphi. Also, they could profitably associate with rich households as well as the courts of autocratic rulers.

The spirit of competition that permeated Greek society from the school age on—we have lists of winners in numerous musical disciplines in local contests for adolescents⁸—naturally sparked innovation at an unprecedented pace. In order to outshine competitors, instruments became both more technically sophisticated and more lavishly decorated. Mechanisms were developed for manipulating the set of available pitches that had before been restricted by a mere five fingerholes per pipe. Hardly anywhere are these halcyon days of woodwind before the modern era documented as stunningly as in the bundle of fragments retrieved from Amanishakheto’s tomb, testifying to a set of instruments truly befitting a royal burial.

Eventually, though, the demands for highly specialized craftsmanship in working metal and bone, and the considerable costs that these entailed, led to the demise of ancient doublepipe culture. When theatrical productions all over the Roman world collapsed under the onslaught of the migration period, on the one hand, and a new religion that was expressly hostile to the traditional show business and banned theater people from its congregations, on the other, doublepipes receded into the shadows of local “folk” cultures, being once more crafted from cheap materials with comparatively simple means. Eventually, most remnants of the traditional dichotomy of lyres and doublepipes were swept away by a new preference for lutes and their bowed variety, fiddles, which for the first time combined a strong continuous sound with the opportunity to accompany one’s own song.

1.2. Construction

In its simplest form, an aulos pipe consists of some kind of straight tube with roughly cylindrical bore, to which a mouthpiece is fitted at one end, and into which fingerholes are drilled at manageable distances. While the Sumerian instrument as well as Egyptian examples limit these holes to the upper side, a typical Greek- or Roman Imperial-style aulos also features a thumbhole, located between those for the index

6. See, e.g., Lawergren 2000; on brass as a costlier alternative to bronze, see Wyslucha 2022.

7. For trumpets, see Jiménez Pasalodos and Holmes 2018; Wyslucha 2018.

8. See, e.g., Hagel and Lynch 2015.

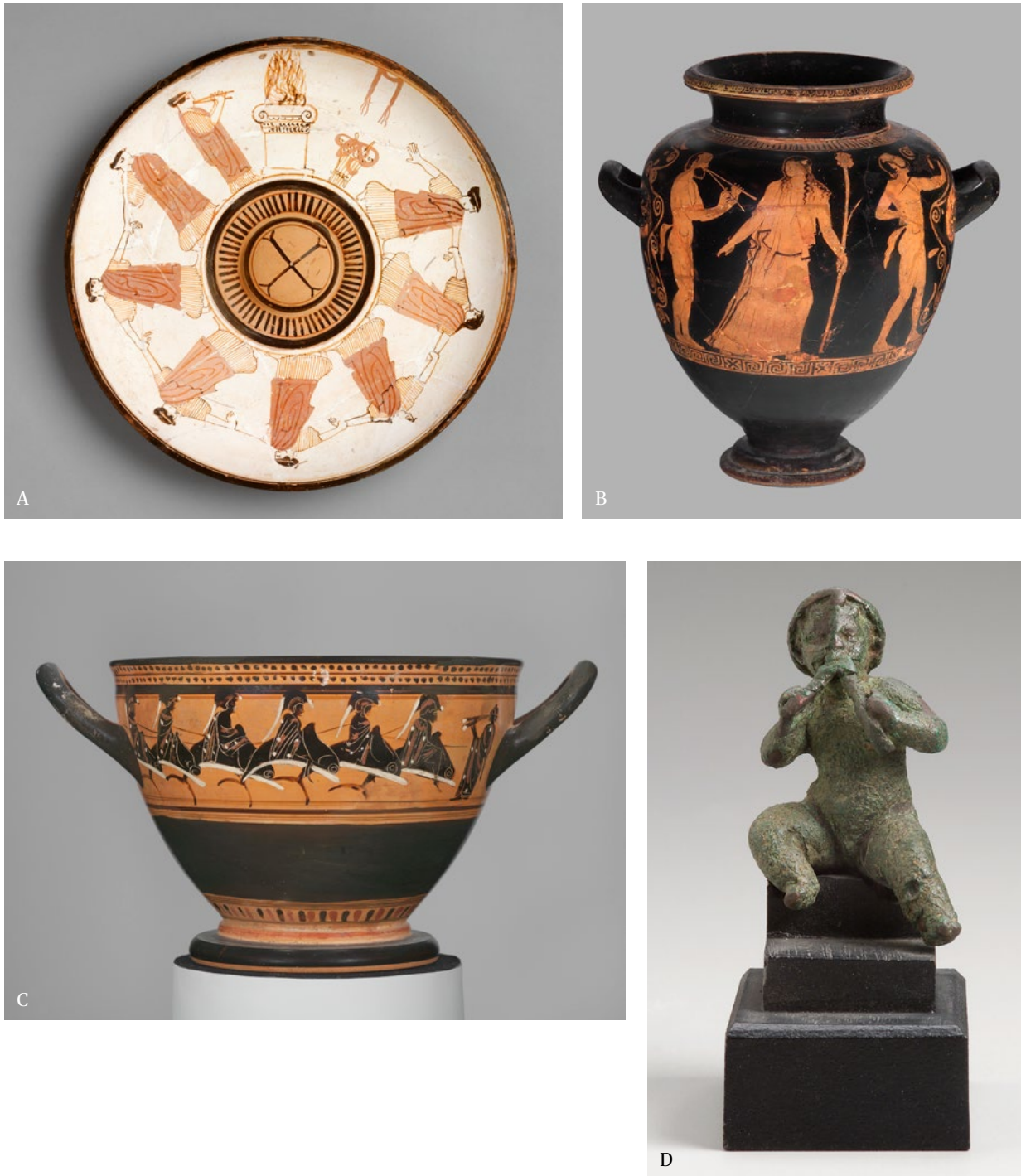


Figure 1.1: (A) Female aulos player leading a dance in front of a burning altar (Attic white-ground libation bowl, c. 450 BCE: MFA Boston 65.908, Edwin E. Jack Fund). (B) Maenad and Satyrs dancing to the aulos (Attic jar, c. 450 BCE: MFA Boston 90.159, anonymous gift). (C) Chorus of dolphin riders, probably from Attic comedy (Attic drinking cup, c. 520–510 BCE: MFA Boston 20.18, gift of the heirs of Henry Adams). (D) Aulos-playing Eros (Bronze, Hellenistic: MFA Boston 72.4440, Hay Collection—Gift of C. Granville Way). Photographs © Museum of Fine Arts, Boston (SC164507, SC40438, SC160010, SC37289).

and the middle fingers (a thumbhole above the index hole, as found for instance on modern recorders, would be unfeasible on a pipe that is held in one hand only).

In order to fit either into the tube, or, if the instrument is particularly thin, over the tube, the reed mouthpiece must terminate in a cylinder. For an optimal exploitation of finger spans, the internal diameter of the mouthpiece should be just as wide as that of the tube itself, so that a specially made socket may

account for the wall of the mouthpiece; this seems to have been the case on more sophisticated instruments. For a “single” or “beating” reed, as are still used in bagpipes and “folk” instruments, a vibrating “tongue” is cut into the side of a length of cane, which is at one side closed by a natural node in the stem. Such tongues can be tuned by scraping as well as sticking lumps of beeswax on it. Double reeds, in contrast, were significantly more difficult to produce and appear to have given rise to a specialized profession. A reedmaker (*glōttopoiós*) would flatten one end of a length of cane, possibly with the help of moderate heat. Before, that tube had been restricted at the desired end point of the blades by a waist, tightly tied with thread, so that the deformation could not spread downwards into the “foot” of the mouthpiece. The Greek writer Theophrastus mentions how reeds were harvested at different times of the year for different playing styles and subsequently exposed to the seasons before being cut down and further processed, optimally producing a matching pair of mouthpieces from a single length of cane.⁹ In older times, these have often been quite long, extending the tube by another 7 cm or so and thus reducing the need for valuable tube material.¹⁰

Simple tubes of cane, wood, or metal could be made in a single piece. The more perishable materials have typically survived only in Egypt,¹¹ including several instruments of Hellenistic design, while only the remains of three wooden pipes have so far been retrieved from Greek soil.¹² Apart from the extremely early Mesopotamian Silver Pipes, only a few examples of simple metal tubing are currently known.¹³ The bulk of finds, hailing from an area that stretches from England and Spain to Tajikistan and Sudan, involves bone tubes, many with metal applications or encasing. Suitable bones were found in the metatarsals of various herbivore ungulates such as deer or donkeys. These leg bones are not only straight but also include a usable relation between minimal external and maximal internal diameter across a significant length, so that cylindrical tubes can be produced from them by drilling and turning on the lathe. However, those lengths would rarely exceed a dozen centimeters. Consequently, tubes needed to be constructed from several sections, taken from more than one animal and joined by spigots and sockets. In the Hellenistic period, the fragile connections were sometimes protected by a bronze ring; the Meroë find is the first securely dated material evidence for bone cores fully clad in metal.

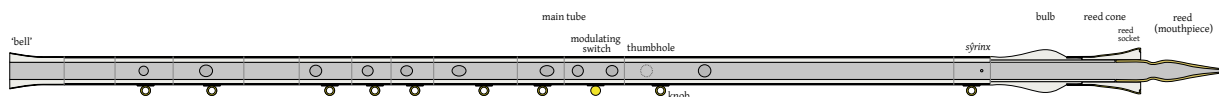


Figure 1.2: Schematic representation of a Roman-period aulos pipe with rotary sleeves and detachable cone.

Another distinctive feature, first attested in Greece and Italy in the sixth and fifth centuries BCE, is what we call the “bulb”: between the cylindrical tube and the reed mouthpiece, the diameter first narrows and then widens to a pear-like shape, a lip on top of which received the reed. The latter subsequently developed into a beaker-shaped extension, also often wound with thread so as not to crack when a reed is tightly pushed in. It has been called “reed cone” or “reed seat” and was probably the part the Greeks called “mortar” (*hólmos*). In otherwise metal-clad instruments, the bulb typically (but not always) exposes its material, while the reed cone is once more protected by a metal encasing (fig. 1.2). In such instruments, the cone was often detachable and probably served as a device for getting the instrument in perfect harmony: by moving it only a few millimeters away from from the bulb, it was possible to compensate for imperfectly tuned reeds (fig. 1.3).¹⁴

9. Theophrastus, *Enquiry into Plants* 4.11.6.

10. Hagel 2020; Wysluca and Hagel 2023.

11. E.g. Sachs 1921: 79–87; Ziegler 1979: 93–96; Bélis 1984; Hagel 2004, 2010, 2014.

12. Two belong to the famous “Elgin aulos” (e.g., Psaroudakēs 2002: 363), now in the British Museum; the third is a badly preserved small pipe from a grave in Athens (Psaroudakēs 2013).

13. Neutsch 1980; Moustaka 2001.

14. Hagel 2012a.



Figure 1.3: Above: bulb and reed cone (with lost metal encasing) of Naples inv. 76894. Below: bulb with reed cone detached of Naples inv. 76892, with traces of a sealing winding, probably of fine thread, on the spigot. From Pompeii, before 79 CE.

The fingerholes on the upper side were normally not arranged in a straight line, but variously displaced to the side for more comfortable playing. Similarly, the thumbholes did not lie exactly opposite the index or middle-finger holes. Whenever it is possible to determine the respective configuration, it may reveal in which hand a particular pipe was held.

Auloi were heterophonic instruments, designed for playing two different notes simultaneously. As a result, the two pipes of a pair never exhibit the same arrangement of fingerholes and are often also of unequal lengths. Nonetheless, we often find a significant overlap between hand positions. On the earliest examples from a Greek cultural environment, the two pipes are offset merely by a single hole, so that the thumbhole of the higher (right-hand) coincides with the index finger hole of the lower (left-hand) pipe. Consequently, it is possible to play five pitches in unison from open toneholes on both pipes, in addition to various fifths, fourths, thirds, and seconds (the use of dissonance is explicitly acknowledged in the sources¹⁵). Later we find offsets of three fingerholes, so that the treble notes of the two pipes play a fourth. An offset of two holes, as it is found on Egyptian doublepipes, was originally predicted for “Dorian auloi” on a purely literary basis,¹⁶ but may now be confirmed by Hellenistic finds from the Bactrian Oxus Temple at Takht-i Sangin (Tajikistan).¹⁷ On highly professional instruments, such as two found in graves in Megara (fig. 1.4), it seems that the fingerholes in the overlapping range may not be tuned in unison, but to different scales, apparently requiring the greatest level of virtuosity in the accompaniment.

15. Most strikingly in ps.-Plutarch, *On Music* 1137c. Relevant passages are collected in Scheltema 1932.

16. Hagel 2009: 408–10.

17. Hagel 2025.



Figure 1.4: Aulos Archaeological Museum of Megara inv. Δ1964 with bronze sliders on bone tube (early third century BCE). Photograph Chrēstos Terzēs, courtesy Archaeological Museum of Megara.

In general, all toneholes are quite large in relation to the bore. As a consequence, cross fingering, a standard technique for accessing various semitones in modern woodwind, hardly ever makes much difference on an aulos: closing or opening additional toneholes below the first open one will typically make only minute differences in the order of less than a tenth of a tone. In order to gain a greater number of functional pitches, ancient players had to resort to other techniques. One is to manipulate the mouthpiece: squeezing it between the lips will narrow the gap between the blades and consequently sharpen the pitch.¹⁸ But this does not work well for low pitches, emitted from holes further removed from the reed, where the resulting difference in overall air volume becomes negligible. Half-holing is more promising: by covering the upper part of a fingerhole, its pitch can be substantially decreased. This must have been the principal way in which the Greeks effected their famous quartertone intervals. Sometimes, for instance on certain fragments from the Oxus find, half-holing is facilitated by specific elongated holes, associated with the middle finger or the thumb.

Other means involve mechanical devices.¹⁹ The later Classical period, about four centuries before the Meroë instruments were produced, saw the introduction of “sliders”: a hole that was outside the reach of the fingers was instead covered by a plate that could be operated by means of a rod. Unlike modern



Figure 1.5: Mechanism of rotary bone tubes, National Archaeological Museum of Taranto (probably Hellenistic). 3D image arranged for cross-eyed viewing. Image Stefan Hagel, courtesy of the MARTA.

woodwind mechanisms, which spring back to their original position once released, such sliders remained in their new position until operated again. Instead of transitorily accessing a novel pitch, they would thus switch the instrument to a different “mode” by permanently changing a bass note. Such sliders are best documented on two instruments from around 300 BCE, found in Megara near Athens (see fig. 1.4), as well as on a bronze model, now lost, of an aulos from the second century BCE.²⁰

An entirely different kind of mechanism dominated the Roman Imperial period. It relies on cylinders that can rotate within each other, so that a tonehole that is drilled through both can be closed by turning the external tubing relative to the internal core. After some experimentation with bone tubes in Hellenistic times, remnants of which have been found in Italy (Taranto, fig. 1.5), Greece (Megara), and once more as far east as Bactria (Takht-i Sangin), a lasting solution was found in mounting two or three layers of very thin metal cylinders on a bone core (fig. 1.6). The innermost would be fixed to the core

18. See ps.-Aristotle, *On Things Heard* 804a.

19. For an overview, see, e.g., Sutkowska 2015.

20. Conze 1903: 7–8 with Tab. 1; Terzēs and Hagel 2022.



Figure 1.6: Four sections with round and rectangular toneholes equipped with rotary sleeves and triangular knobs. Bone core and two layers of metal are easily discernable at the round tonehole, where the core has become dislodged by a couple of millimeters. MFA Boston 24.3579, from the Meroë find (parts 099–071–095–001).

and replicate its hole patterns, while the external layers could be adjusted to open various configurations of toneholes. Most typically, each external “rotary sleeve” would operate a single opening, but in certain cases, longer sections might open and close several at once or serve as modulating switches between two or more holes. We will encounter examples below, including the most complex documented modulating “switch.” At any rate, the magnificent skills exhibited by the makers of such instruments, both regarding the working of bone and metal, were hardly surpassed by any other known technology from before modern times.



Figure 1.7: Ring-shaped knob on a fragment in the National Archaeological Museum of Naples. 3D image arranged for cross-eyed viewing. Image Stefan Hagel, courtesy of the MANN.

Since bare cylinders would be almost impossible to turn in single-handed action, small “knobs” were soldered on each rotating sleeve, which could take on various shapes. In addition to globular and ring-shaped variants, which are paralleled in Pompeii (see fig. 1.7), finds from Meroë, both those from Amanishakheto’s tomb that are the subject of this publication and others found earlier in the city,²¹ introduce a triangular form (fig. 1.6; see ch. 5 below).

Both kinds of mechanism, sliders and rotary sleeves, have also been employed for controlling a special kind of very small hole close to the mouthpiece.²² Being called *syrix* (“whistle, flute”), it served the purpose of a modern speaker hole: by destroying the soundwaves of the fundamental frequency, it forced the instrument into a higher mode of oscillation, either a twelfth or even more than two octaves above its normal pitch. In most cases, however, such *syrix* holes, which are already well attested in the Classical

21. Southgate 1915.

22. Sliders: Megara 1965 (Terzēs and Hagel 2022); sleeve: National Archaeological Museum of Naples inv. 76892 (Howard 1893: 49). On the *syrix* in general, see Hagel 2012b (now partially outdated thanks to the publication of the Megara find).

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period, are not found equipped with any kind of special mechanism. We must then assume they were normally closed with some plug of bone, wood or wax.

From the first century CE on, paintings, mosaics, and stonework depict aulos tubes sprouting fancy applications from their sides, such as small beakers and lengthy “spikes.” These do not concern us here—though some “side tubes” form part of the Meroë cache, they are of a different nature, as we shall see.

2 The Context: Meroë

Denise Doxey

2.1. The Site of Meroë

The region currently called ancient Nubia was known in antiquity as Kush. It encompassed what is now the southernmost part of Egypt and the northern part of Sudan (fig. 2.1). The Sudanese site of Meroë, located about 209 km north of Khartoum near the modern town Kabushiya, was the capital of the sprawling empire of Kush from at least the fifth century BCE to the early fourth century CE, giving the latter part of this era the designation Meroitic period.¹ Its location, in a fertile region on the Nile's east bank, was ideal for many reasons. Seasonal rainfall and large-scale water management projects enabled both agriculture and animal herding to thrive. Trade routes extended out from the Nile Valley, positioning Meroë as an economic hub for exchange between central Africa and the Mediterranean world. Abundant natural resources included gold, copper, iron ore, semiprecious stone, minerals, ebony, and high-quality clays.² Wildlife provided exotic materials that were desirable in Egypt and other nations to the north, such as ivory, animal pelts, and ostrich shell. War elephants traveled north to Ptolemaic and Roman Egypt, ultimately headed for Rome.³

In the preceding Napatan period (750–332 BCE), when the capital of Kush lay further north at Napata near present day Jebel Barkal, royal inscriptions had used the Egyptian language and hieroglyphic script. Texts of the Meroitic period, however, were written in the local language and script, Meroitic (see fig. 2.8 below).⁴ While the basic sounds and some vocabulary have been deciphered, the language is still not fully understood, leading scholars to rely heavily on archaeology and iconography in attempting to interpret Meroitic history.

Meroë began as a rural settlement, but increased in density throughout the first millennium BCE and was a major urban center by the end of the third century BCE (fig. 2.2). Much of it remains unexcavated or poorly published, but it is nevertheless possible to discern the city's general layout. It included separate administrative, residential, religious, and industrial quarters.⁵ The best understood section, now dubbed the "Royal City," was surrounded by thick, fortress-like walls and housed the main temple of the state god, Amen, along with additional temples, at least one palace, and numerous storage facilities.⁶ Near the palace and the fortification wall was an enigmatic sanctuary featuring a large water tank, leading the excavator, John Garstang, to misidentify it as a Roman Bath (fig. 2.3).⁷ Many architectural elements of the structure reflect influence from the Mediterranean world and an association with Dionysos, whom the Nubians associated with the local lion god Apedemak.⁸ The exact function of the complex remains unclear, but it may have served as a center for rites relating to the Nile's annual flood or for royal rejuvenation.

On the outskirts of the city were extensive ironworking facilities, evidenced by the remains of smelting furnaces and massive slag heaps.⁹ Meroë was at the forefront of the relatively new industry of iron

1. Grzymski 2021: 545–61.

2. Grzymski 2021: 547.

3. Török 2009: 105.

4. Rilly and de Voogt 2012.

5. Grzymski 2021: 552–58.

6. Garstang 1912: 47–48; Grzymski 2021: 553–54.

7. Garstang 1913: 77–81; Wolf and Onasch 2010: 97–98.

8. Sackho-Autissier 2010b.

9. Humphris 2020: 981.



Figure 2.1. Map of Sudan. © Museum of Fine Arts, Boston.

production. Meroitic craftspeople and artisans were also leaders in developing other new technologies such as enameling, enabling them to create magnificent jewelry and other adornments.¹⁰

In the desert to the east of the city, next to the modern town of Begrawiya, lay three cemeteries, designated by their excavator, George A. Reisner, as Begrawiya North (Beg. N), Begrawiya West (Beg. W) and Begrawiya South (Beg. S) (fig. 2.4).¹¹ The southern and western cemeteries are the earliest, and with

10. Markowitz and Doxey 2014: 132–33, 150–51.

11. Dunham and Chapman 1952; Dunham 1957, 1963; Yellin 2020: 564.

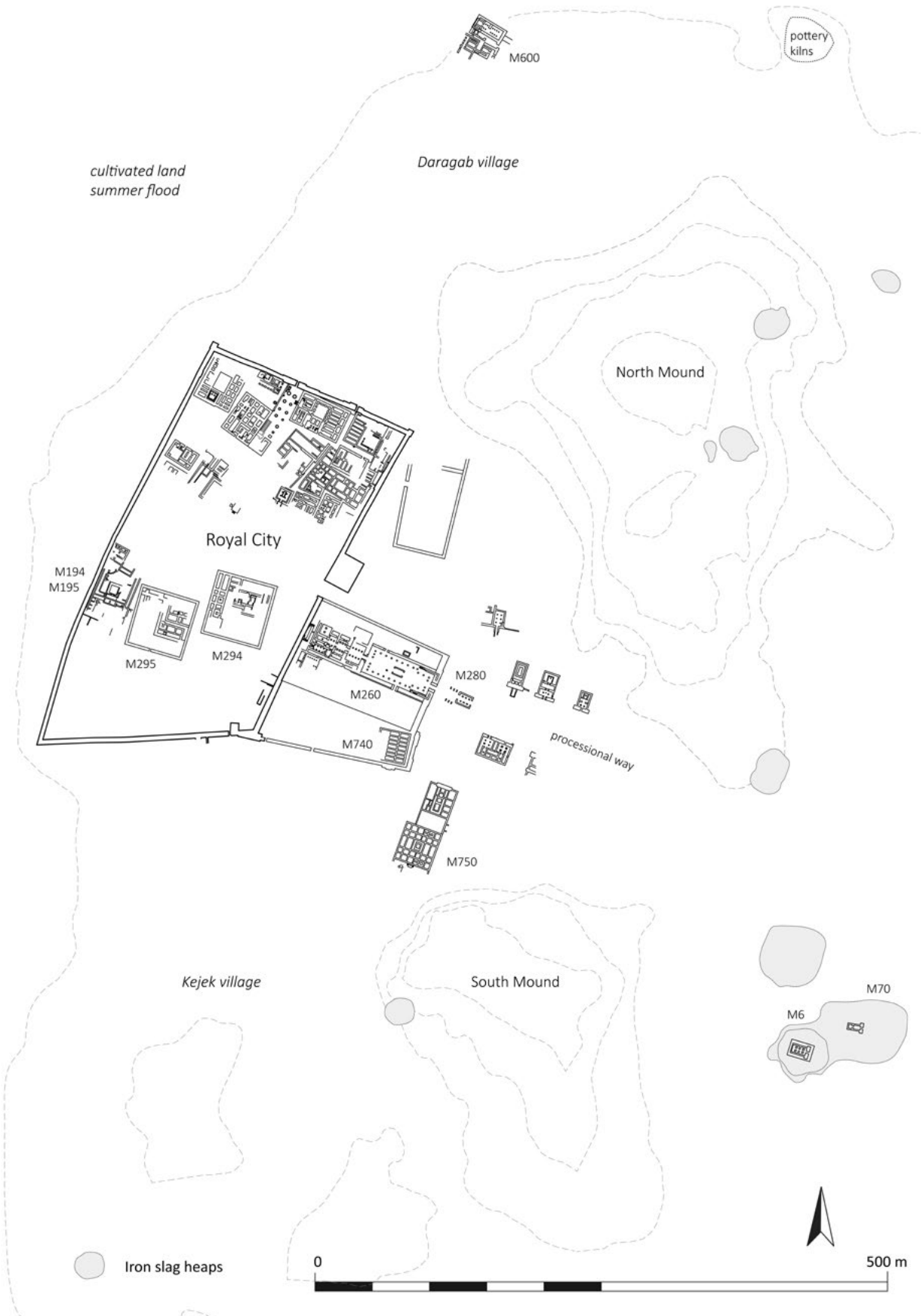


Figure 2.2. Plan of Meroë City. © Pawel Wolff.



Figure 2.3. Excavation of Meroë site 195 (“Royal Baths”), 1912. JG-M-LA/31. © University of Liverpool.



Figure 2.4. Begrawiya North pyramids. February 12, 1921. Photograph by Mohammedani Ibrahim Ibrahim. Harvard University–Boston Museum of Fine Arts Expedition A3056_NS. © Museum of Fine Arts, Boston.

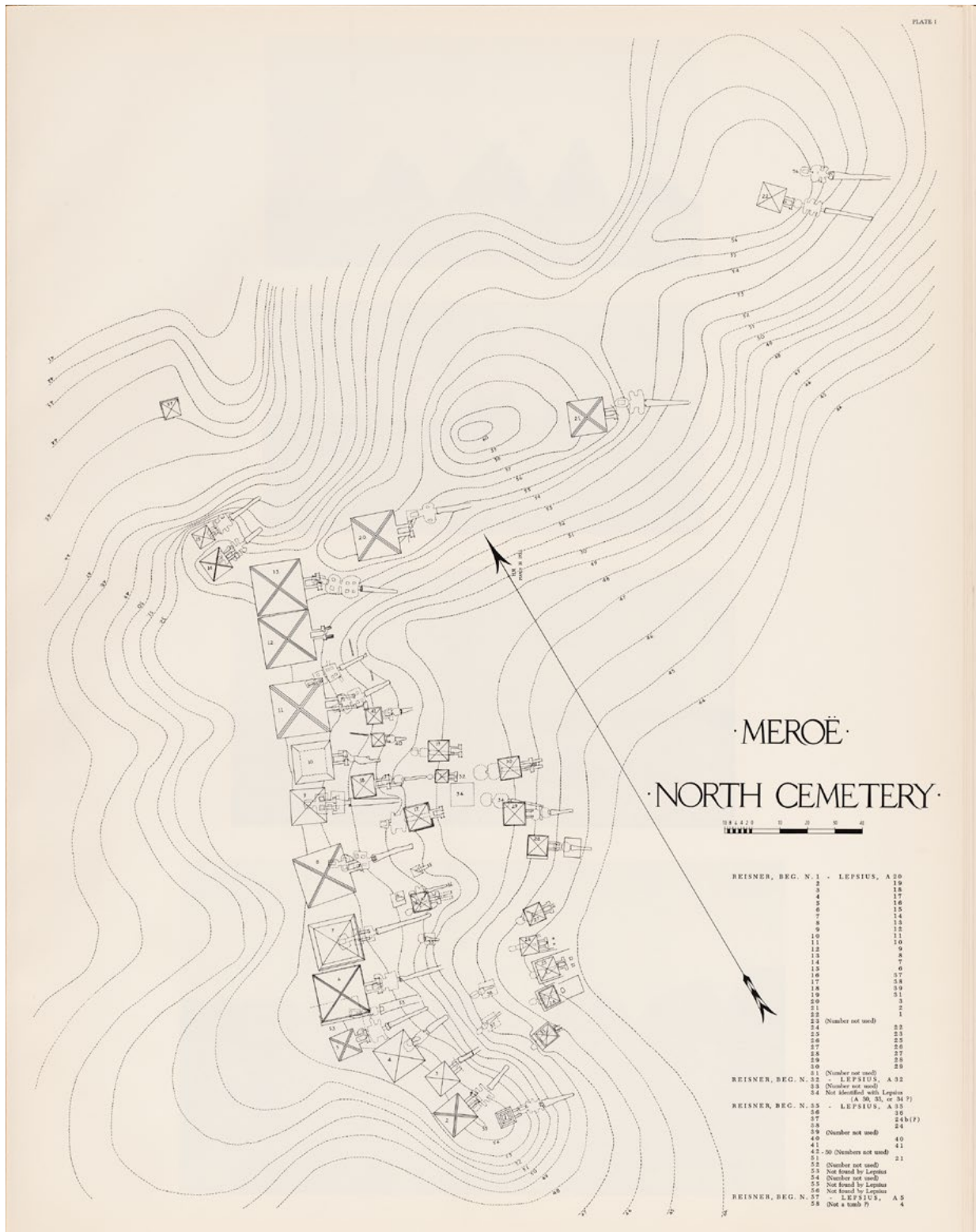


Figure 2.5. Plan of Begrawiya North Cemetery. Chapman and Dunham, *Royal Cemeteries of Kush III* (Boston: Museum of Fine Arts, 1952), pl. 1. © Museum of Fine Arts, Boston.

only a few exceptions the tombs of Beg. S predate the Meroitic period. In the early third century BCE, the northern cemetery became the new burial ground for royalty (fig. 2.5), while the western cemetery housed the pyramids of senior officials and other elite dignitaries.¹²

12. Dunham 1963: 1.

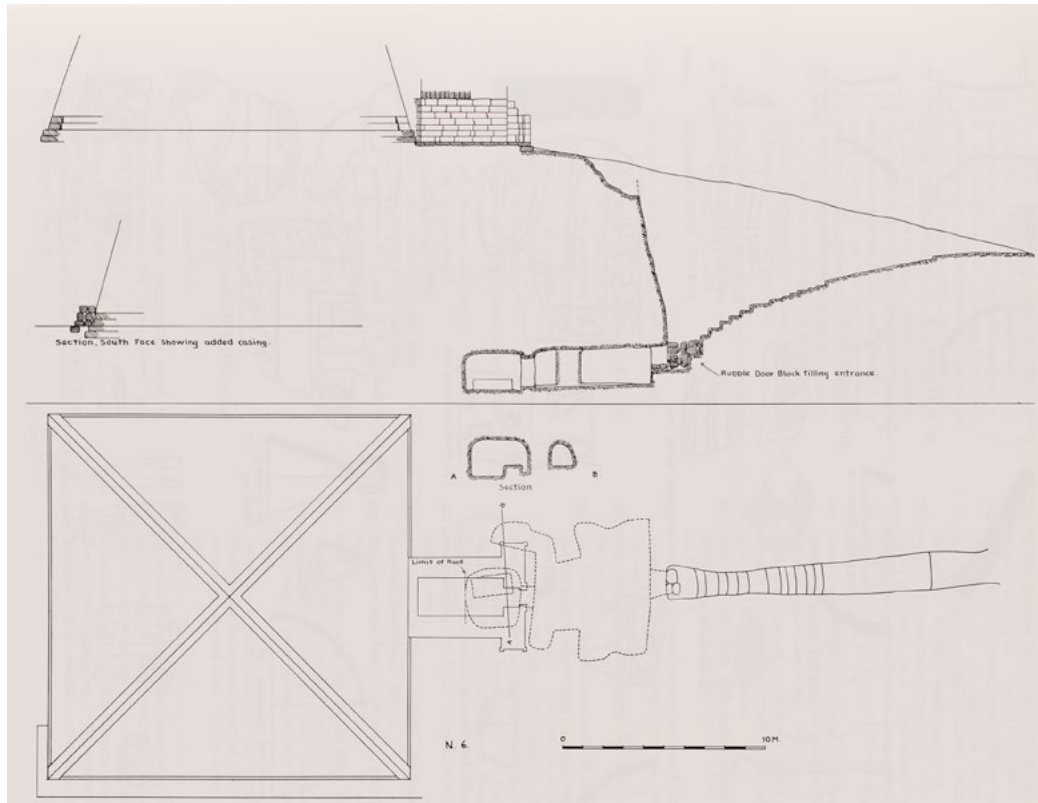


Figure 2.6. Plan & section of Begrawiya North 6. Dunham, *Royal Cemeteries of Kush IV* (Boston: Museum of Fine Arts, 1957), fig. 72. © Museum of Fine Arts, Boston.

The design of Meroitic royal pyramids is distinctive (fig. 2.6). Constructed of a solid rubble core encased in carefully dressed sandstone blocks, they are very steep-sided (68–73 degrees¹³), with relatively small footprints when compared with the better-known pyramids of Egypt. Attached to the pyramids' east faces were memorial chapels made of sandstone blocks and fronted by temple style pylons depicting the ruler about to dispatch bound foreign captives. The interior walls bore scenes of the deceased ruler receiving funerary gifts in the presence of gods and goddesses (fig. 2.7). Although very few traces of color survive, the scenes were originally plastered, painted, and sometimes gilded. The chapels served as the location for funeral feasts, ceremonies, and rituals, as well as the offering of food and beverages to sustain the tomb owners in perpetuity.¹⁴ In the absence of translatable inscriptions from the Meroitic period, tomb decoration provides invaluable evidence about funerary religion, kingship, administration, the royal court, and the chronology of Meroë's rulers.¹⁵ The scenes also illustrate the costumes and regalia associated with royalty, including long robes, fringed shawls, and cap-like crowns and fillets adorned with a rearing *uraeus* cobra in front and streamers at the back. Kings and queens apparently wore large quantities of elaborate jewelry such as earrings, broad collars, necklaces, pendants, rings, armlets, and stacks of bracelets. Actual jewelry that has survived supports the veracity of the tomb-chapel scenes.

Below the pyramids were rock-cut subterranean burial chambers that could not be reached from the interior of the pyramids themselves. Instead, they were accessed by a stairway entered from outside the pyramid, often at some distance away. Here, the royal remains lay, sometimes on elaborately decorated sandstone benches featuring funerary deities, and surrounded by precious grave goods. These underground chambers were sealed after the burials were complete, and were not intended to be revisited. Sadly, almost none survived the ravages of tomb robbers both ancient and more recent.

13. Yellin 2020: 567.

14. Yellin 2020: 564–65.

15. Yellin 2020: 563–64.

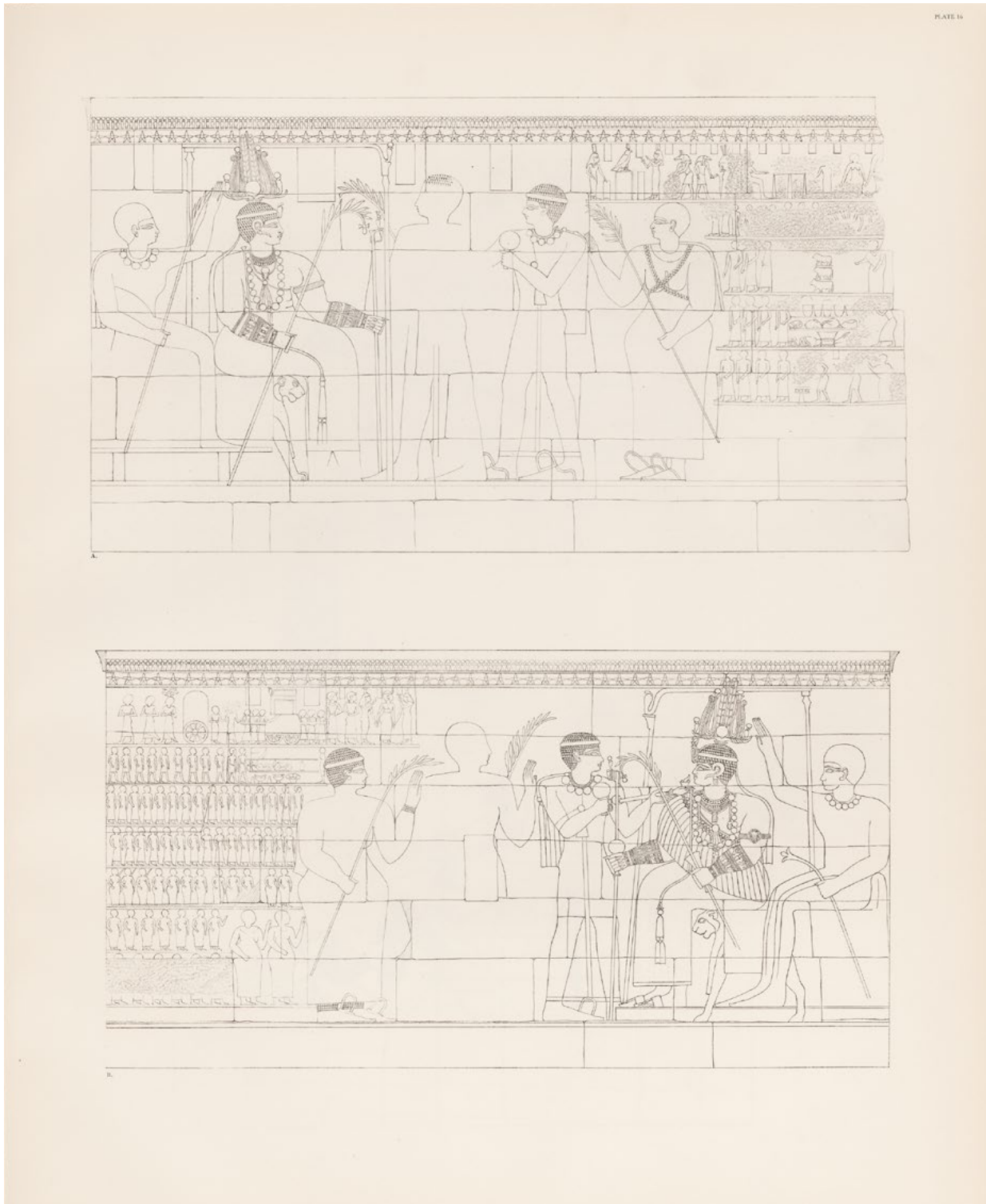


Figure 2.7. Begrawiya North 6, north and south walls of chapel. Chapman and Dunham, *Royal Cemeteries of Kush III*, pl. 16. Original drawing by Suzanne Chapman. © Museum of Fine Arts, Boston.

Excavators have found evidence for funerary festivities in the spaces just outside the sealed burial chambers, including animal bones, trays, pottery, and drinking vessels.¹⁶ It was in exactly this location in one of the largest Meroitic pyramids, Beg. N number 6, the burial place of Queen Amanishakheto, that the auloi were uncovered.

16. Yellin 2020: 564.

2.2. Queen Amanishakheto

Relatively little information survives about the life and reign of Queen Amanishakheto. Nevertheless, what evidence there is attests to her great importance. She was one of four queens who ruled the Meroitic kingdom during the last half-century BCE and the first half-century CE, a period when the Meroë was at the height of its power.¹⁷ Nubian queens bearing the title of *kandákē* in Greek or *candace* in Latin were previously understood to have been rulers, but their status remains unclear. They might instead have been the king's sister or mother.¹⁸ However, Amanishakheto, along with her immediate predecessors, Nawidemak and Amanirenas, and her successor, Amanitore, were independent rulers in their own right.¹⁹

Amanishakheto's palace at Wad Ban Naga, which once stood at the center of a city and a complex of temples, is among the largest known Nubian palaces.²⁰ Remains from other sites offer further glimpses of the queen. A pair of stelae were found at Naga, an important royal city, religious center, and trade emporium located about 40 kilometers south of Meroë. They portray the queen in the presence of two of the most prominent Meroitic deities, the lion-god Apedemak and his consort Amesemi. On the larger, Apedemak sits enthroned on the right.²¹ Amanishakheto stands before him wearing the elaborate jewelry, long gown, fringed shawl, and close-fitting cap that identify her as a ruler. Amesemi stands behind her, supporting her elbow. On the smaller stele, Amanishakheto, again clad in royal regalia, stands facing Amesemi (fig. 2.8). The queen raises her arm in worship as Amesemi embraces her.²² The backs of both stelae are inscribed with religious texts in the Meroitic script (fig. 2.9). Amanishakheto's name also appears in the Egyptian hieroglyphic characters on blocks from Temple T at the site of Kawa.²³

Amanishakheto's pyramid, Beg. N 6, was once among the most impressive tombs at Meroë (fig. 2.10). The queen appears twice on the pylon of her funerary chapel in the traditional role of a king. Dressed in full royal regalia, she spears a group of bound foreign enemies (fig. 2.11). The figure to the left of the entrance wears a tall, feathered crown and holds a bow and arrow. That on the right wears a simpler crown while driving a spear into the necks of her captives. Both wear lavish and abundant jewelry, including earrings, broad collars, and elaborate stacked bracelets.

Amanishakheto's greatest claim to fame today might in fact be her jewelry. A number of European travelers visited her pyramid before the first scientific excavations by the Harvard University–Boston Museum of Fine Arts Expedition in the 1920s. The tomb remained largely intact until 1835 when Giuseppe Ferlini, an Italian physician who served in the Egyptian army, arrived at Meröe in search of its fabled treasure.²⁴ Ferlini and his workers proceeded to demolish the pyramid from the top down in their unsuccessful quest for a room or rooms inside the superstructure. Eventually Ferlini must have found the correct way to access the chamber from the outside, but he kept the true location a secret for the rest of his life, claiming instead that he had found a small space at the top of the structure. Inside the burial chamber was a breathtaking cache of jewelry, including five pairs of hinged bracelets, sixty-seven signet rings, nine hair ornaments, four earrings, dozens of pendants and amulets, a broad collar, and many other pieces (fig. 2.12).²⁵ After dismissing his workers to keep them from learning about the treasure, he spirited it out of Sudan, ultimately selling the bulk of it to the king of Bavaria and the remainder to the Egyptian collection that had recently been formed by the King of Prussia. Today, most of the material is housed in the Staatliche Museum Ägyptischer Kunst in Munich and the rest is the Ägyptisches Museum und Papyrussammlung in Berlin.

17. Haynes and Santini-Ritt 2012: 182–84; Sackho–Autissier 2010a: 178–79.

18. Sackho–Autissier 2010a: 178–79; Haynes and Santini-Ritt 2012: 180; Morkot 2012: 123–24.

19. Haynes and Santini-Ritt 2012: 182–83.

20. Onderka et. al. 2013: 57–62; Haynes and Santini-Ritt 2012: 183.

21. Rilly 2010: 157

22. Wildung 2004: 180–81.

23. Macadam 1949: 117, pl. 35.

24. Lacovara and Markowitz 2019: 10–15.

25. Lacovara and Markowitz 2019: 158–71.



Figure 2.8. Sandstone stele showing Queen Amanishakheto with the goddess Amesemi (front). Reign of Amanishakheto, late first century CE. From Naga Khartoum, Sudan National Museum SNM31338. Photograph by Christian Décamps. © Musée du Louvre, Dist. GrandPalaisRmn.

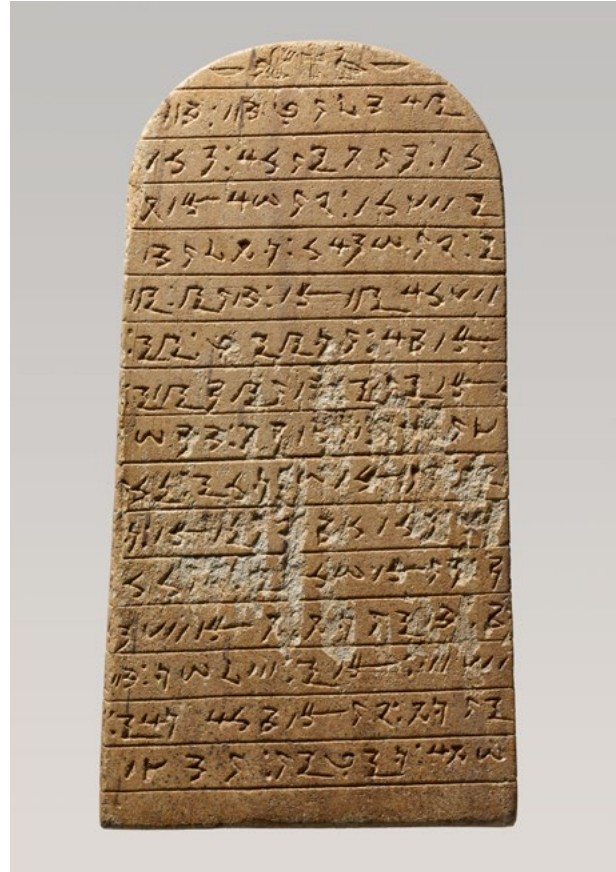


Figure 2.9. Sandstone stele showing Queen Amanishakheto with the goddess Amesemi (back). Reign of Amanishakheto, late first century CE. From Naga Khartoum, Sudan National Museum SNM31338. Photograph by Christian Décamps. © Musée du Louvre, Dist. GrandPalaisRmn.

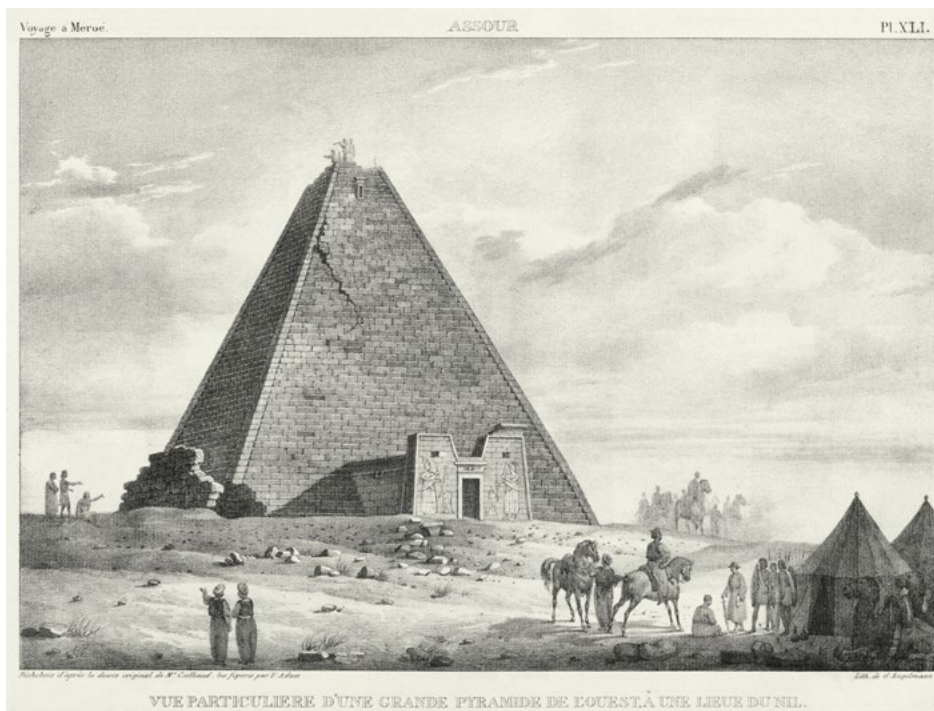


Figure 2.10. Frédéric Cailliaud, “Pyramide de la candace Amanishakheto, Méroé, nécropole Nord, tombe N 6,” in Cailliaud, *Voyage à Méroé* ([Paris], 1826–27), pl. 41.

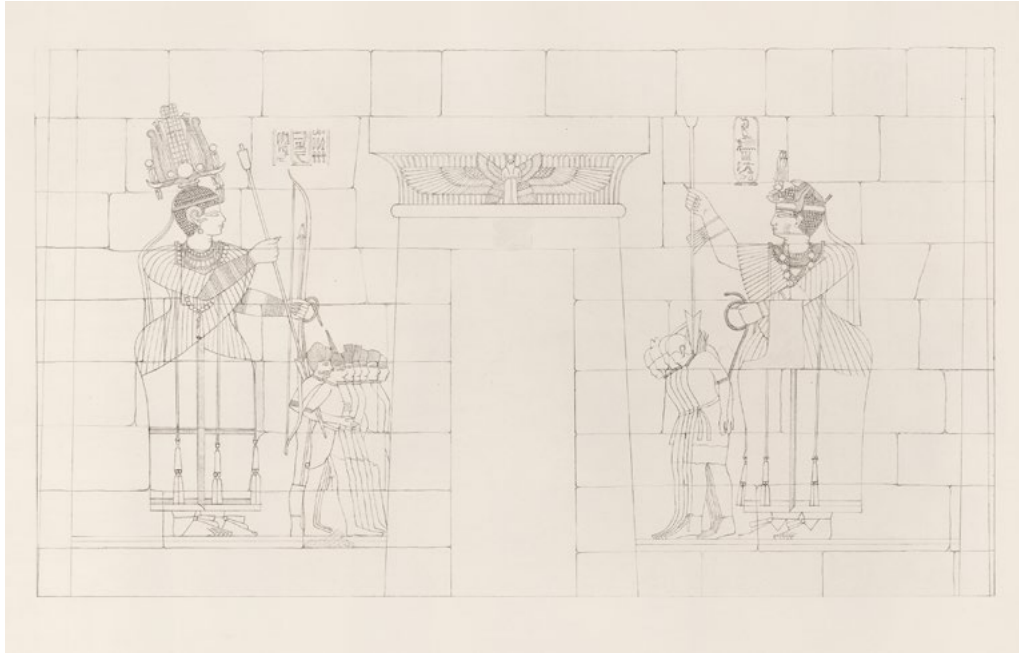


Figure 2.11. Begrawiya North 6, pylon. Chapman and Dunham, *Royal Cemeteries of Kush III*, pl. 17. Original drawing by Suzanne Chapman. © Museum of Fine Arts, Boston



Figure 2.12. Clasp bracelet with image of Mut. Gold with enamel inlay. Reign of Amanishakheto, late first century CE. From Meroë, Beg. N 6. Munich, Staatliches Museum Ägyptischer Kunst, ÄS 2455. Photograph by Marianne Franke. © SMAEK, Munich.

2.3. Recovering the Auloi

Between 1905 and 1945, the Harvard University–Boston Museum of Fine Arts Expedition, directed by George A. Reisner, excavated at more than twenty sites in Egypt and Sudan (fig. 2.13).²⁶ Having already carried out work in the royal and elite Nubian cemeteries at Kerma, Nuri, el-Kurru, and Jebel Barkal in the years from 1916 through 1919, Reisner turned his attention to Meroë beginning in the spring of 1920.²⁷ The first season was primarily a brief survey of the North and South Cemeteries, with some excavations in the South Cemetery. Reisner noted the poor state of preservation in the North, where treasure hunters inspired by Ferlini’s finds had destroyed the upper portions of most of the pyramids.

26. Manuelian 2023.

27. Manuelian 2023: 442–45.

Excavations resumed in earnest the following January. Reisner, along with Dows Dunham and Said Ahmed Said Diraz, continued to excavate the cemeteries through 1923 (fig. 2.14). Although Reisner was a pioneer in scientific excavation for his day, his methods would not meet modern-day standards. At times, he employed more than 150 local workers, clearing multiple pyramids simultaneously.²⁸ In late March of 1921, the team began clearing the stairway leading to Queen Amanishakheto's burial chamber. On the 23rd, at the foot of the stairway in debris at the entrance to the burial chamber, they made a surprising discovery (fig. 2.15). Reisner wrote, "In the original filling about a meter above the floor and 7–8 meters from the east end, found a number of bone tubes cased in bronze plate. These have holes and may be a flute (or similar)"²⁹ Due to the objects' fragility, the excavators removed them only on March 25th, still encased in their matrix of hardened earth (fig. 2.16).³⁰ There is no record of their condition after removal from the soil nor of their state when they reached Boston. The contents of the burial chamber itself had been mostly reduced



Figure 2.13. George A. Reisner. June 26, 1933. Harvard University–Boston Museum of Fine Arts Expedition D-B7512. © Museum of Fine Arts, Boston.

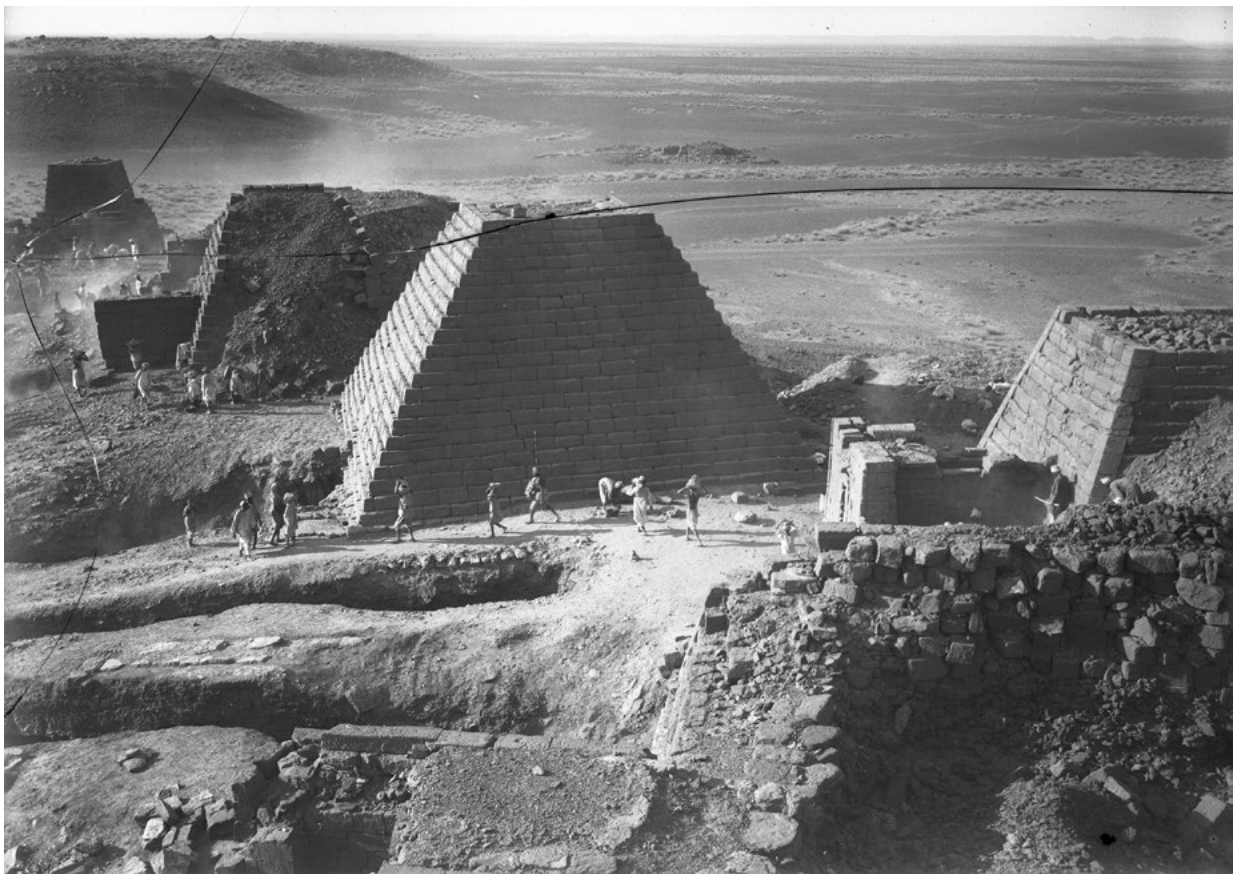


Figure 2.14. Excavations at Begrawiya North Cemetery from the top of Pyramid 7, March 13, 1922. Photograph by Mohammedani Ibrahim Ibrahim, © Museum of Fine Arts, Boston. Harvard University–Boston Museum of Fine Arts Expedition B4076_NS.

28. Manuelian 2023: 453, 485.

29. HU-MFA Expedition Diary, March 23, 1921.

30. Dunham 1957: 109.

Figure 2.15. Begrawiya North 6, entrance after removal of door block. Photograph by Mohammedani Ibrahim Ibrahim, March 25, 1921. Harvard University–Boston Museum of Fine Arts Expedition C9217_NS. © Museum of Fine Arts, Boston.



Figure 2.16. Auloi in situ. Photograph by Mohammedan Ibrahim Ibrahim, March 25, 1921. Harvard University–Boston Museum of Fine Arts Expedition C9218_NS. © Museum of Fine Arts, Boston.

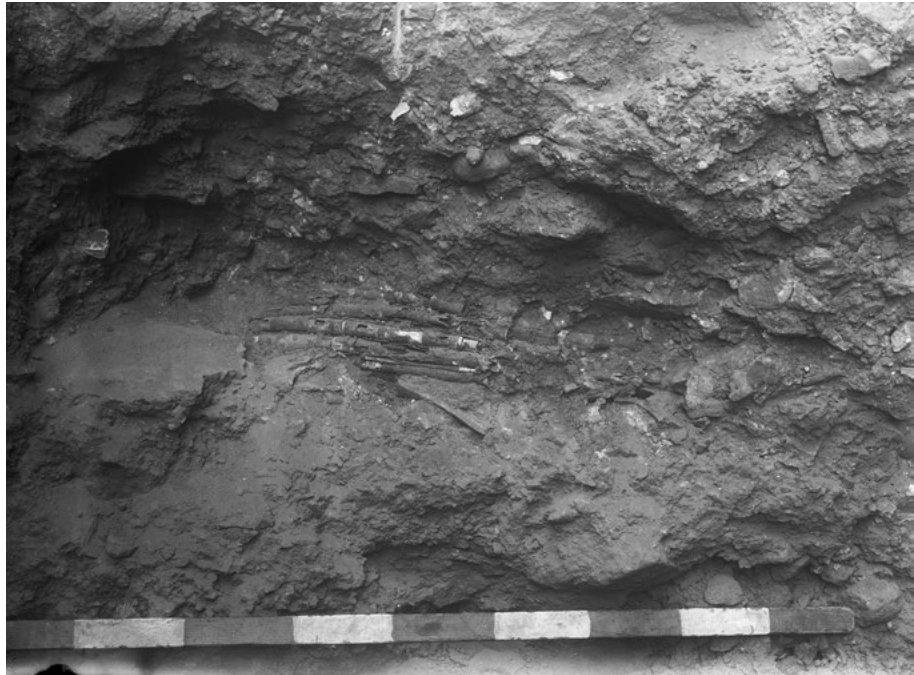


Figure 2.17. Ring with glass bezel. Gold and glass. Reign of Amanishakheto, late first century CE. From Meroë, Beg. N 6. © Museum of Fine Arts, Boston.



to fragments of faience and pottery, but the excavators did find a well-preserved bronze bell and a gold signet ring inlaid with a glass bezel (fig. 2.17).

2.4. Auloi and Dionysus in Kush

Exactly how and when auloi first reached Nubia is unclear. No examples have survived from earlier than the first century BCE. By that time, auloi had been popular musical instruments in the ancient Mediterranean world for centuries. Representations of them are ubiquitous on Greek vases, where they appear in a variety of contexts including athletic events, rituals involving dancers and processions, symposia, and the cult of Dionysos and his retinue (fig. 2.18). By Roman times Dionysos, by virtue of his role as a god of fertility and hence rebirth, was seen as an appropriate subject for the decoration of sarcophagi, where processions featuring Dionysos, satyrs, maenads, musicians, and animals appear with some frequency (fig. 2.19). It is in this context that auloi can be linked specifically to funerary contexts in Ptolemaic and Roman Egypt and eventually in Nubia.

Examples of actual auloi had already been found at Meroë prior to Reisner's discovery of Amanishakheto's pyramid. In the city of Meroë, Garstang discovered a group of fragments from at least five aulos pipes of different sizes (see ch. 8 with fig. 8.1).³¹ Based on the description published by T. L. Southgate in 1915, they seem to have been remarkably similar to those found in Amanishkheto's tomb and it is possible that two sets arrived in Meroë together, perhaps with the same musician or musicians. Unfortunately, the current location of the auloi found by Garstang is unknown.

An attempt to understand how auloi found their way into funerary practices as far away as Meroë has been facilitated by the recent work on relations between Ptolemaic and Roman Egypt and Kush by scholars such as Stanley M. Bernstein, László Török, and Aminata Sackho-Autissier. It has long been known that Meroë had ties to the Classical world. Classical authors described Greeks traveling to Meroë as early as the second and first centuries BCE.³² Influenced by these ancient writers and by discoveries made at Meroë by Garstang between 1909 and 1914, including architectural elements with Greek inscriptions, historians initially overstated the significance of Greek influence on Meroë. Ensuing research has corrected this misunderstanding and provided a much more nuanced picture of the interconnections between Meroë and the Mediterranean world, focusing on Hellenistic and Roman Egypt as the principal point of interaction. Amanishakheto's auloi can best be understood as part of this process, along with Meroë's adoption of Hellenizing imagery and architectural elements.

As noted above, the water sanctuary found by Garstang in the Royal Enclosure at Meroë contained statues and architectural details clearly inspired by Greek and Roman iconography, leading him to mistakenly call it the "Roman Baths." These finds provide strong evidence for Meroë's adoption of some elements of Classical religious practice.³³ For example, a statue of a nude female that is now in Munich, the so-called Venus of Meroë, might have been



Figure 2.18. Red-figure drinking cup (kylix) depicting a symposium. The Proto-Panaitian Group 510–500 BCE. Henry Lillie Pierce Fund 01.8018. © Museum of Fine Arts, Boston.

31. Southgate 1915: 13–14.

32. Török 2009: 1–2.

33. Török 2009: 139–88; Baud 2010: 85; Wolf and Onasch 2010: 97–98.



Figure 2.19. Marble sarcophagus with triumph of Dionysos, 215–225 CE. From the island of Proconnesus in the Sea of Marmara near Istanbul. William Francis Warden Fund 1972.650. © Museum of Fine Arts, Boston.

intended to represent Aphrodite (fig. 2.20). A sculpture of a reclining, draped man now in Copenhagen is believed to have been a personification of the Nile (fig. 2.21).³⁴ While the artists who created these works were clearly familiar with Hellenistic types, they worked with local sandstone in a distinctively local style, with heavier proportions, round faces, and large, almond-shaped eyes. Sackho-Autissier and others have convincingly argued that the inhabitants of Meroë associated the Nile floods with Dionysos, a belief adopted from Ptolemaic Egypt.³⁵ As Török observes, the water sanctuary seems to have shared certain features with those of the sacred lakes found at Egyptian temples and the symbolic Nile source at Elephantine.³⁶

Also among the statuary from this aquatic complex is a group of musicians playing Classical-style musical instruments, including a nude boy holding an aulos, now in the Petrie Museum in London (fig. 2.22). This is one of very few representations of aulos in Meroitic art to have survived. Both the pose and the youth's nudity are reminiscent of symposium attendees and followers of Dionysos seen in Greek and Roman art. In addition to the water complex, other clearly Dionysiac motifs in faience appear throughout Meroë city, such as enigmatic cylinders showing dancers in Classical attire, including a goat-legged figure who may be Pan or a satyr.³⁷ As Bruce Trigger observed, "The satyr, dancing, and possible music-making that are portrayed in a Classical style are reminiscent of the cult of Bacchus or Dionysius, who was identified syncretistically with the Egyptian and Meroitic god Osiris."

34. Török 2009: 161.

35. Sackho-Autissier 2010b: 203.

36. Török 2009: 172.

37. Trigger 1994: 389–96.

Figure 2.20. The “Venus of Meroë.” From Meroë, “Royal Bath,” second to third century CE. Sandstone with stucco and paint. Munich, Staatliches Museum Ägyptischer Kunst, ÄS 1334. © SMAEK, Munich.

The choice by Meroitic rulers to adopt Dionysos into their own royal cults was almost certainly influenced by contemporary practices in Ptolemaic Egypt. Alexander the Great had been deified after his death and portrayed as Dionysos incarnate. The Ptolemies in turn claimed descent from the god, associating themselves with him increasingly over time.³⁸ The later Ptolemies used the title of Neos Dionysos, “new Dionysos,” portraying themselves as the god’s living manifestation, just as their pharaonic predecessors had claimed to embody Osiris and Horus.³⁹ Ptolemy XII, who lived not very long before the time of Amanishakheto, was known by the sobriquet Auletes, “the aulos player.”

The adoption of Dionysos and his cult may also reflect an economic reality, as wine was one of Meroitic Nubia’s major imports from Hellenistic and later Roman Egypt. Grapevines became a popular artistic motif. Images of Dionysos and wine-related activities have been found in buildings from the reign of Amanishakheto and her contemporaries at sites outside Meroë. For example, two faience frieze fragments showing grape vines and wildlife come from her palace at Wad Ban Naga.⁴⁰ The Harvard-Boston excavations provided further evidence of Dionysos in mortuary rituals at Meroë itself. Among imports

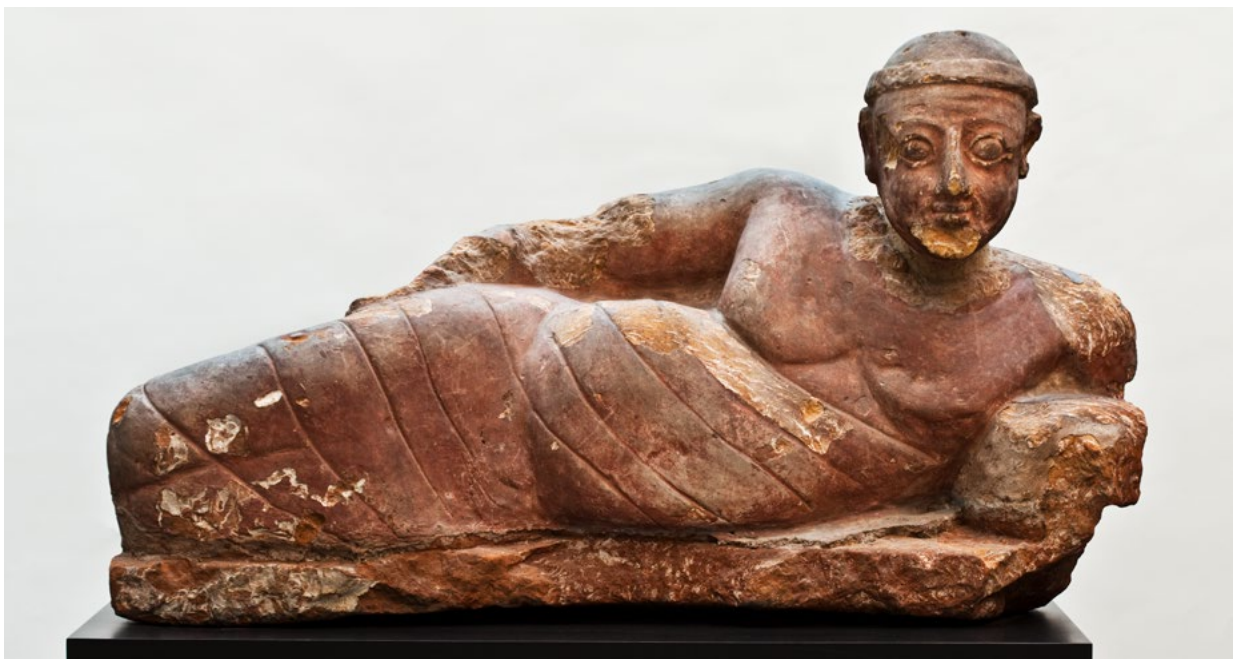
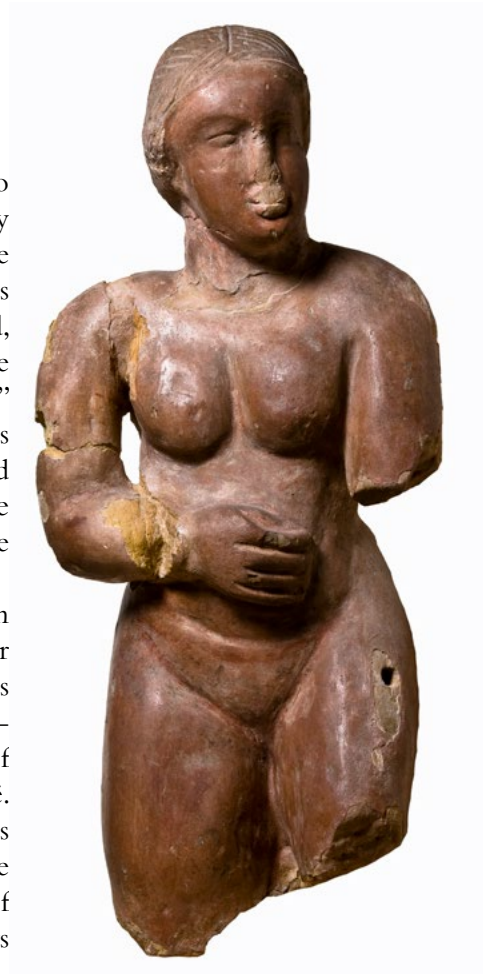


Figure 2.21. Statue of a reclining man. Third century CE. Sandstone with stucco and paint. From Meroë, “Royal Bath.” Copenhagen, Ny Carlsberg Glyptotek Æ.I.N 1484. © Ny Carlsberg Glyptotek.

38. Huzar 1995: 3099–3102; Koenen 1993: 70.

39. Huzar 1995: 3102.

40. Sackho-Autissier 2010b: 206.



Figure 2.22. Meroë site 195, statue of a youth playing an aulos, 1912. JG/M/L/49. © University of Liverpool.

predating the reign of Amanishakheto are strainers, cups, and other metal vessels used to prepare and serve wine (fig. 2.23), allowing scholars to trace the practice of wine consumption by the Kushite elite to as early as the third century BCE.⁴¹

Other finds demonstrate the continuity of Dionysiac funerary ritual at Meroë in the generation immediately after Amanishakheto. The tomb of the prince Ariankharer, son of King Natakamani of the first century CE, contained a pair of heads of Dionysos in bronze and silver, along with a variety of other body parts from the same statues (fig. 2.24).⁴² The presence of these sculptures so close in time and place to Amanishakheto's auloi strongly suggest that Dionysos played an active role in royal burial rituals during her reign.

In later Meroitic times, evidence for the cult of Dionysos remains strong, and motifs such as grape vines and clusters are relatively common on painted pottery, such as a jar from Kerma now in the Museum of Fine Arts, Boston (fig. 2.25). They also appear with some frequency on pottery from Karanog. One jar from Karanog, now at the Penn Museum in Philadelphia, depicts three somewhat comical dancing figures, each of whom wears horns and a tail and plays an aulos (fig. 2.26). Between them are wine jars in stands. Sackho-Autissier has described these dancers as incorporating iconography of satyrs and of the god Bes, both deities associated with music, dance, and joy.⁴³



Figure 2.23. Silver strainer, fourth century BCE. From Meroë, Beg. S 6. Harvard University—Boston Museum of Fine Arts Expedition 24.874. © Museum of Fine Arts, Boston.

41. Manzo 2006: 83–84; Török 2009: 107–8.

42. For recent publications, see Sackho-Autissier 2010b.

43. Sackho-Autissier 2010b: 206.



Figure 2.24. Bronze head of a statue of Dionysos with silver and shell. 150–50 BCE. From Meroë, Beg. N 5. Harvard University—Boston Museum of Fine Arts Expedition. 24.957. © Museum of Fine Arts, Boston.



Figure 2.25. Decorated spheroid ceramic jar. Second century CE. From Kerma K18/2. Harvard University—Boston Museum of Fine Arts Expedition 13.4038. © Museum of Fine Arts, Boston.



Figure 2.26. Globular ceramic jar with Dionysiac dancers. Second to third century CE. From Karanog, tomb 112. E8216. © Penn Museum.

Music and dance have been shown to have played a role in temple and funerary ritual as early as the Napatan period, as indicated by the musicians who appear on the “Musician walls” in the hypostyle hall of temple T at Kawa, built during the reign of Taharqa (seventh century BCE).⁴⁴ Here, a priest carrying a brazier leads a group of trumpeters, drummers, harpists, and singers. The same type of drums appears in Meroitic times as well, including on a fragmentary cup found by Garstang in Meroë city and in a scene from the funerary chapel of Queen Shanakdakheto at Meroë (Beg N. 11), only a generation removed from Amanishakheto.⁴⁵ From a later context comes a bronze basin from the fourth century CE tumulus burial of a ruler at Hobagi bearing a scene of dancers accompanied by drummers and other musicians.⁴⁶ These scenes have been interpreted as ritual dances performed by officials or members of the royal family during the king’s funeral in order to facilitate his transformation into Osiris.⁴⁷

44. Macadam 1955, pl. 53.

45. Disseaux, Reinold, and Lenoble 1997: 53.

46. Disseaux, Reinold, and Lenoble 1997: 50.

47. Disseaux, Reinold, and Lenoble 1997: 54–55.

In light of this evidence, the appearance of auloi in the tomb of a Meroitic queen living in the Nile Valley at a great distance from the Mediterranean should perhaps seem less surprising. The playing of auloi was a regular practice in the cult of Dionysos, who by this time in Egyptian history had transcended his role as a god of wine and revelry to become a protector of rulers and of rebirth in the afterlife. Cross-cultural entanglements between Kush and Ptolemaic and Roman Egypt brought his cult south to Meroë. Music and dance already played a part in Nubian royal funerary and temple rituals well before Amanishakheto's time. What remains remarkable is the size and complexity of this astonishing set of instruments so far from their place of manufacture.

3 Research History

Stefan Hagel

3.1. Aulos Research

When the pipe fragments were found in the staircase leading to Amanishakheto's tomb, enough was known about the Graeco-Roman aulos to identify them as belonging to this class of instruments. After centuries of scholarly uneasiness with the unfamiliar concept of doublepipes, Albert A. Howard had laid the groundwork for modern aulos studies with a seminal article published in 1893. Apart from examining many relevant texts, Howard studied four pipes that had been found in Pompeii, measured them, created playable models and discussed the pitches these produced. Perhaps most importantly, he described the mechanism of rotary sleeves, highlighting an unexpected level of technical proficiency on the part of the ancient instrument makers. Some years before, Victor-Charles Mahillon had already teamed up with François-Auguste Gevaert to inspect the same instruments and create working models for the Musical Instruments Museum in Brussels.¹ At first, Mahillon, informed by ethnographic parallels of cylindrical reedpipes ("clarinets") from the Mediterranean, equipped it with a single "beating" reed, as did Howard. After encountering undisputable iconographic evidence for ancient double reeds on journeys to Carthage and Rome, however, Mahillon switched to such a reed, crafted following East Asian parallels.²

Slider mechanisms became known almost at the same time, at first on a bronze aulos model discovered in Pergamum and described by Alexander Conze.³ Fragments with rectangular toneholes as well as the specific triangular knobs and even a teardrop-shaped fingerhole surfaced a little later, during John Garstang's excavations at no other place than the city of Meroë, and were discussed by Thomas Lea Southgate.⁴ At the time of the excavation of Amanishakheto's tomb, therefore, practically all technical aspects of the retrieved instruments were well documented, and their identification unproblematic. However, next to nothing was known about diverse instrument types, let alone typical aulos scales. Consequently, the highly fragmented nature of the find, combined with insufficient documentation of the relative placements of the parts, prevented any attempt at a reconstruction. This was still recognized by Nicholas B. Bodley (before 1945: Nikolai Bessaraboff; fig. 3.1),⁵ when he finally embarked on examining and publishing the material in the course of his comprehensive survey of the MFA's musical collection:

The condition of various parts of the Meroe auloi is such that a complete restoration, even of a single instrument, is not possible. This is, of course, a great loss since there still remain several technical questions which, if settled in a positive way, would eliminate many moot points with respect to Graeco-Egyptian music of the period near the birth of Christ. (Bodley 1946: 218)

Such unconditional capitulation—in fact, Bodley did not even venture to restore larger portions—may nonetheless appear surprising, given that he thought he had the key to ancient aulos design in Kathleen

1. Mahillon 1890: 306–8; Gevaert 1881: 280–304.

2. Mahillon 1893: 432; 1900: 294, 391. Howard (1899) reached the same conclusion, but bent the texts to fit a modern oboe or bassoon reed produced from a folded strip of cane instead of a complete length of tube flattened at one side, as Mahillon rightly inferred. For aulos double reeds, see also Byrne 2000; Wysłucha and Hagel 2023.

3. Conze 1903: 7–8.

4. Southgate 1915.

5. On Bodley's life and general achievements, see Boyden 1971.



Figure 3.1: Nicholas Bodley, interviewed by Carleen Hutchins in 1967. Photograph kindly provided by Darcy Kuronen.

Schlesinger's just published opus magnum on the topic.⁶ Alas, it seems that the key did not fit. At any rate, Bodley's detailed descriptions, which remained the only account of the find for eighty years and included some important measurements, were of great consequence, alerting the public both of the unique objects from ancient Kush specifically and of the intricacies of ancient musical craftsmanship in general.

Schlesinger's conception of ancient music, which Bodley accepted wholesale, was based on the principle of equal physical distances between toneholes, which consequently produced series of unequal intervals, geometrically increasing with pitch while implementing simple mathematical structures. Though such an idea played into a general desire to grasp the elusive art of ancient music as a lost paradise, untainted by the decadence of modern tuning conventions, it flew in the face of everything that the Greeks themselves said about their scales and has ever since proven incompatible with the archaeological evidence no less than the texts. It is a well-noted weakness of fringe or emerging fields that indifference to material evidence in favor of a modern author's original conceptions stands good chances to be published.⁷ Schlesinger's book appeared in 1939, when Bodley had started studying the pieces. Still in the same year, Reginald P. Winnington-Ingram, who had published an insightful monograph on the question of Greek modes not long before,⁸ passed a polite but unmistakable verdict on Schlesinger's theory;⁹ but it may have come too late for Bodley to take into account. Even so, it remains surprising that an organologist of Bodley's standing and experience would have turned a blind eye not only to the unmistakable fact that it proved impossible to connect the fragments to any larger structures with identical tonehole spacing, but also to the varying distances of holes on some of the longer preserved pieces that he described.

The fate of the cache during the next fifty years is poorly documented. When Maurice Byrne, in the course of an ambitious quest to collect all available aulos archaeology, first visited the MFA and compared

6. Schlesinger 1939.

7. Two examples from both before and after Schlesinger's book may illustrate the point. Curtis 1914 posited the hypothesis that one aulos bulb in a pair hid a recorder-like device, making its pipe a duct flute, while the other was hollowed out to serve as a windcap for a reed like on a crumhorn. The two pipes would sound alternately in spite of both being continuously held in the mouth (any kind of harmony needed to be reserved for modern Western music history). Najock 1996 ventured the idea that the bores of the instruments narrow stepwise toward the mouthpiece, allowing overblowing at significantly smaller intervals than the (rough) twelfth expected for cylindrical instruments. Both theories were borne out of the desire to expand the melodic range of the aulos; neither would have survived exposition to the evidence known at each period.

8. Winnington-Ingram 1936.

9. Winnington-Ingram 1939: "Too often her interpretations are based on a complete misunderstanding of the context, or else they assume what should be proved." See also Landels 1981: 300–301; West 1992: 96–97.

the boxes with Bodley's descriptions, he noted down: "Between 1946 and my arrival on 6 Nov 1996, objects had been moved around and damaged."¹⁰

Meanwhile aulos studies had progressed. In the mid-sixties, a German monograph by Heinz Becker joined in the discussion.¹¹ Like Schlesinger, Becker was on safer ground with music-ethnological parallels than close reading of ancient literature, so that his sometimes astute argument is unfortunately marred by misunderstanding the literary sources. For instance, Becker revived the theory of single reeds as the typical form of aulos mouthpieces, exerting a lasting influence on reconstruction efforts at least in the German-speaking world.

Knowledge of the material evidence, especially of relatively early bone instruments, was greatly furthered by John G. Landels.¹² He also speculated about the intervals that might be obtained with suitable reeds, using a simple mathematical approach that equated the relations between distances on the instrument with (inverse) relations of frequencies. Starting from one postulated pure interval such as a fourth, the necessary length of the mouthpiece can thus be calculated, and from this the rest of the intervals.¹³ The method works quite well between large fingerholes of equal size and roughly equal spacing, as are typical for the early finds, but gives misleading results when applied to fingerholes of different size, very diverse spacing, and to the pitch obtained from the end of a pipe. It was applied to further finds by Richard J. Letters, among these the four from Pompeii that had already been studied by Howard and Gevaert.¹⁴ Letters's assumptions were rightly criticized by Martin L. West in his groundbreaking handbook *Ancient Greek Music*, who went on to provide his own figures for ten of the simpler pipes, most of them comprising only six or even five holes, but including also the "Louvre aulos," an undated wooden pair from Hellenistic or Roman Egypt with seven and nine, respectively.¹⁵ Even so, none of them yielded a sequence of pitches that ancient music theory would have explained. Even though West passed wise judgment on a number of vexed questions, the time was still not ready in the early 1990s to appreciate the inherently heterophonic nature of the aulos in full. No undisputable pairs had yet been published, and even though West appears to accept the Louvre aulos as forming a pair, the offset of three fingerholes between the playing ranges of its pipes did not keep him from envisaging aulos music as basically unison. It was not until three years later that Andrew Barker, arguing from various angles, revived the notion of intervallic harmony as a pervasive element of ancient music.¹⁶

Landels's legacy was taken up by Stelios Psaroudakēs, who meticulously documented numerous early finds and established consistent relations between dimensions and "handedness," showing that the left hand typically held the longer, lower pipe.¹⁷ The later, Roman-period type with rotary sleeves was less lucky. A jumbled-together item in the National Archaeological Museum of Athens was described and rearranged, probably still wrongly,¹⁸ while a complex section that surfaced in London in extraordinary condition appeared too short to extrapolate the design of the instrument it had belonged to.¹⁹ An inclusive publication of preserved finds with mechanisms and corresponding iconography is anticipated, having only recently been prepared by Olga Sutkowska.

Due to limitations of the experimental method, a profound investigation of aulos scales had to await the widespread availability of computer technology. While a faithful reproduction would in principle reproduce the correct pitches, the nature of reedpipes thwarts such an approach. First, since the original

10. M. Byrne, copies of personal notes kept in the Museum of Fine Arts, Boston.

11. Becker 1966.

12. Landels 1963, 1964, 1968.

13. Landels 1981, including an account of the shortcomings of this (and, partially, any) mathematical approach.

14. Letters 1969.

15. West 1992: 94–101. Intervals for the Louvre aulos had been proposed before as an approximation of low-integer ratios (Bélis 1984), though on the basis of flawed measurements and unsuitable methodology, ignoring the required presence of a reed mouthpiece. An experimental approach is reported by Byrne 2000: 280 n. 8.

16. Barker 1995. Barker 2002 expertly revolves around many questions concerning the auletic art in its wider context of Greek music culture.

17. Psaroudakēs 2002, 2008, 2013, 2014, 2020.

18. Masaraki 1974.

19. Lawson and Wardle 1998.

mouthpieces are invariably lost, one would have to experiment with a large number of configurations in order to determine the musically most likely, above all where two pipes are involved. More importantly, as Curt Sachs had already cautioned, modern experimental performers, especially with lip-controlled double reeds such as typically used on ancient auloi, would inevitably bend the pitches to suit their own expectations of a musical scale.²⁰ A computer model overcomes both problems: on the one hand, the machine is entirely impartial to hearing conventions (or can be told to look for particular scales that are alien to Western ears). On the other, pitches and intervals are quickly calculated and compared over the entire spectrum of possible effective reed lengths. The respective formulae for the effects of tonehole sizes, adjacent open and closed holes, wall thickness and irregularities in the bore having long been established,²¹ I have first created dedicated aulos software, connected to a database of finds, in 1997. Besides quite accurately predicting the pitches for a given pipe and reed mouthpiece, it was found useful to implement automated searches for reed configurations producing optimal “harmonicity,” to express the predicted frequencies in terms of modern and ancient musical notation as well as the intervals between them in terms of cents (hundredth parts of a semitone), to make them audible through the computer’s sound system, and to enable quick comparison with the various musical scales mathematically described by ancient authors. Being originally applied mostly to the early finds, the first published results obtained by this software concerned the Louvre aulos.²² Subsequently it was applied to the four prominent pipes from Pompeii, which for the first time led to a proposal how these would relate to the system of ancient “keys” (*tónoi, trópoi*), and a discussion whether certain aspects of their fine-tuning and sleeve design might be related to melodic conventions detectable in surviving melodies from the Roman period.²³ Another wooden doublepipe from Egypt followed, not unlike the Louvre aulos, but smaller, with a single bronze ring and pipes of dissimilar lengths, which may allow to connect its design with a particular fragment of Roman-period instrumental music.²⁴

At any rate, instruments from the latter period with an almost modern-looking design including rows of semitones with occasional whole-tone intervals in between are more easily comprehended than the earlier examples with more equally spaced toneholes, dating from the Archaic to the Hellenistic period. West associated such a similarly-spaced design with the importance of three-quarter tone intervals in early aulos-focused music theory, reported by Aristoxenus. A potential alleyway to their understanding was later opened up by the partial reconstruction of the respective pre-Aristoxenian systems, which seemed to have aligned the various ancient modal scales around the top notes of some novel modulating types of aulos.²⁵ The abstract data gained from such a reconstruction seemed to align with note-use statistics from fragmentarily surviving Hellenistic melodies (in sharp contrast to the later ones) and probably with Conze’s aulos model mentioned above. Hard archaeological confirmation was first claimed to be found in two almost completely surviving instruments from Megara that were examined, published and reconstructed by Chrēstos Terzēs.²⁶ Adopting Byrne’s insight that the “double bulbs” seen on ancient vases, which had long been haunting aulos literature, actually comprised the stem of a long reed mouthpiece, the typical early designs could also be reconciled with the scarce information on early Greek music preserved by ancient writers.²⁷

Many of these results have meanwhile been put to practice by a growing international community of aulos enthusiasts. The Louvre aulos in particular has become the novice’s typical instrument, while more professional musicians experiment with the early types. Exploration of sleeve-equipped instruments, which are much more expensive to produce in the original materials, is only just gaining track—and may be expected to expand now I have started to provide working 3D-printed copies of such mechanisms.

20. Sachs 1921: 82.

21. Benade 1960.

22. Hagel 2004; cf., with corrected measurements and refined methodology, Hagel 2014, 2021.

23. Hagel 2008, 2012a.

24. Hagel 2010.

25. Hagel 2009a, where, however, the old supposition that Hellenistic pipes had rotary sleeves is foolishly repeated.

26. Terzēs and Hagel 2022.

27. Hagel 2020.



Figure 3.2: Maurice Byrne inspecting the Meroë aulos find. Photograph © Museum of Fine Arts, Boston.

At any rate, the unprecedented progress in aulos studies over the last twenty-five years could inspire new hope to wrest from the Meroë find whatever musical secrets it might hold. Part of such a program was already laid out by Byrne after his careful inspection in 1996 (fig. 3.2):

The Meroe pipes were found in a damaged state, but approximately seven meters (twenty-three feet) of tubing, plus enumerable [*sic*, apparently for “innumerable”] fragments, corresponding to at least sixteen different pipes, of at least four different types were recovered. The remains are now in too fragile a state to handle. They are in urgent need of conservation so that they can not only be preserved, but also fully interpreted. There are enough differences between the pipes (diameters, wall thicknesses, finger-hole distributions, closure mechanisms, external profiles, materials, etc.) to ascribe fragments to different pipes and to join or associate extended sections together.

It will also be necessary to compare the restored sections with other finds (from Pompeii, in Greece, Turkey, Slovenia, London, etc.), in order to accurately restore the entire set of pipes. Copies could then be made and, as enough is now known about the reeds used on auloi, these copies could be played.”²⁸

Byrne himself, however, never proceeded along the path he had envisaged; given the amount of fragmentation and the brittle state of many important parts, he had to content himself with using the find to illustrate some general arguments about aulos design.²⁹ His optimism, it now seems, was not fully warranted: without the use of the computer, a restoration of even a single instrument would hardly appear viable. Also, as will become clear in a later chapter, Byrne greatly overestimated both the number of instruments and the detailed structural parallels with other finds on which he hoped such a restoration could be based.

3.2. The Meroë Auloi Project

In 2012, Olga Sutkowska, who had taken part in the investigation of auloi from Pompeii three years before and was mainly interested in the mechanical aspects of ancient doublepipe culture, arrived in Boston together with music archaeologist Adje Both for a new inspection and cataloguing of the fragments (fig. 3.3). Agreeing with Byrne that a large effort by aulos specialists would be required to make substantial progress, while physical conservation would be prerequisite for any attempt in this direction, she encouraged Darcy Kuronen, then Pappalardo Curator of Musical Instruments at the MFA and vividly interested in giving the unique find the attention it deserved, to proceed in this direction.

28. Byrne 1997.

29. Byrne 2000, 2002.



Figure 3.3: Olga Sutkowska inspecting the find in 2012. Photograph © Adje Both.



Figure 3.4: From left to right: Susanne Gänsicke, Peter Holmes, Stefan Hagel, and Olga Sutkowska, working on the find in 2015. Photograph © Museum of Fine Arts, Boston (SC323865).

The plan won the support of Matthew Siegal, Chair of Conservation and Collections Management, and conservator Susanne Gänsicke was tasked with treating, rehousing and, as far as possible, reassembling the pieces, during a period from 2013 to 2016. At the same time, X-ray images of nearly all metal tubes and a number of bone parts were produced, and selected metal pieces were subjected to elemental analysis by energy-dispersive X-ray fluorescence spectroscopy. The details of these processes and other examinations will be presented in the next chapters; suffice it here to say that, without Susanne's incredible success in reestablishing parts that had already broken during burial, in the soil, or during excavation, any music-archaeological endeavors would have remained futile.

In preparation for such a second stage of the project, Darcy Kuronen had contacted the Austrian Academy of Sciences, at that time the only institution to have studied comparable instruments in depth. In 2015, the MFA generously invited a team comprising Olga Sutkowska, renowned music archaeologist Peter Holmes from Middlesex University, London, and the present author for a first study session (fig. 3.4). Though Peter Holmes's work has otherwise been focusing mostly on ancient horns and trumpets, we had already been collaborating on reconstructions of auloi with metal rotary sleeves from Pompeii and Ptuj (ancient Poetovio), in the framework of an international project creating a touring exhibition on



Figure 3.5: Joining sections guided by one of the excavation photographs. Photograph © Susanne Gänsicke, Olga Sutkowska, and Stefan Hagel.

past European music.³⁰ Under Susanne Gänsicke’s supervision, we sighted the material from technical and organological perspectives, sorting the existing tubing by internal and external diameters as well as core material, looking for thumbholes as pieces indicative of individual pipes, piecing together possible relations between the long sliders and the musicians’ fingers, and looking for the original locations of the three severed “chimneys,” short side tubes that would have lowered the pitch of a fingerhole.

Soon it became clear that external patterns would never allow joining the plethora of individual pieces to longer segments. Only rarely would ragged ends of broken bone suggest joints between original tube sections. Wooden cores had shrunk, become detached, warped, and disintegrated beyond any hope for conservation. Metal sections, finally, when complete, would exhibit smooth ends whose original connections one might only guess on the basis of corrosion patterns, which are often very distinct around the cylinders’ circumference, but hardly ever decisive. After all, in many cases adjacent sections had already been separated in the ground.

In addition to external evidence, musical probabilities needed thus to be taken into account from the very start. I therefore devised a grid of lines roughly corresponding to the relative distances between toneholes for the semitone steps of ancient musical notation, based on a tuning standard that had already been deduced from surviving melodies in the nineteenth century, and which had recently been corroborated from other auloi as well as the proportions of string instruments in ancient art (fig. 3.6).³¹ Glued together from a number of sheets, this grid would serve as the foremost working space in almost all larger-scale restoration attempts during the following nine years. Its lines would quickly allow to judge the musical options for a given disposition of fingerholes: where, on the instrument, would a piece have to go in order to produce a sequence of tones, or alternatively of semitones, or perhaps of something like the rough three-quarter tone intervals typical for early instruments? Of course, one needed to take other factors into account, such as diverse hole diameters or the effect of a “chimney,” but with the necessary caution the tool proved of invaluable help, especially during the first years, before it became possible to set up precise computer simulations quickly.

More decisive support came from the two black-and-white photographs that were taken at the excavation, in two different stages (figs 4.5 and 4.6 below). Unfortunately, these show only a relatively

30. *European Music Archaeology Project (EMAP)*, see <http://www.emaproject.eu/>.

31. Hagel 2009a: 68–95.

small part of identifiable pieces, thirty on one and twenty on the other. But they are of breathtaking detail, allowing the identification of items guided by fine details of corrosion and small cracks in the metal or bone. After Olga Sutkowska had realized their potential, some hours of collaboration produced two extended lengths composed of some of the more mysterious pieces with especially wide bore and partially rectangular toneholes, distributed at unusually large distances and sometimes on different sides (fig. 3.5). Being unsuitable for fingering and evidently designed for a very low bass region, lower than any known aulos would have reached, these parts caused a lot of puzzlement. Were they remnants of customizable drone pipes whose upper part had vanished, being made of wood?

At the end of our first visit, it had become clear that, apart from those curious pieces, we were dealing with three different general instrument types, each represented by four pipes and therefore two instruments. The sliders had been mounted on what we termed the “long pipes,” which were also substantially thicker. The slenderer pieces, in turn, belonged either to simpler instruments with wooden core, which, albeit encased in a layer of bronze, featured no mechanisms, or to another set of complex instruments, with rotary sleeves and an abundance of toneholes. Substantial lengths, it seemed, were missing only from the long pipes, especially at the ends of two of them.

It took another visit, later in the same year, to realize that those two missing bass sections were in fact provided by the two existing bass sections. Obvious though this may appear in hindsight, it required abandoning one of our most-beloved criteria for separating instrument types in the first place: it had to be accepted that the internal diameter of some auloi could vary over their length, with distressing consequences for an accurate prediction of pitches.

At this point we decided to publish—besides updates on the MFA’s project website—a first report, detailing conservation efforts and preliminary music–archaeological considerations.³² A year after it had appeared, a more thorough discussion of the latter, including a first interpretation of some instruments, was presented at the conference of the *International Study Group on Music Archaeology* (ISGMA), subsequently published in the group’s series.³³ It was on the basis of this stage that Peter Holmes completed a first reconstruction in wood and bronze, which was shown along the originals in an exhibition at the MFA titled “Ancient Nubia Now,” from October 2019 through January 2020.³⁴

However, it soon turned out that some of the conclusions had been based on incomplete evidence, when a closer survey of old photographs and Bodley’s data revealed that one rather inconspicuous length of plain tubing could not possibly be identified with any existent part. It had firmly corroded onto a larger piece and may have collapsed in an effort to separate the two at some point, leaving behind some remnants on the other tube, which we could connect to another splinter only years later.

In spite of fast early progress, numerous questions thus remained, which could only be expected to find answers in a long-term project, requiring funding beyond what any of us might initially have anticipated. The continuation of our research was therefore envisaged as part of a five-year project, which placed the Meroë find in the context of a larger quest for traces of music that may not have ascribed to the “globalized” standards of originally Greek music culture that increasingly permeated the Mediterranean from the period of Greek colonization over the conquests of Alexander up to the Hellenized Roman Empire. Kindly funded by the European Research Council (ERC),³⁵ and starting in 2018, the project was eventually extended to 2024 due to travel restrictions during the COVID pandemic that greatly delayed our research. Meanwhile Susanne Gänsicke had taken on the position of Head of Antiquities Conservation at the J. Paul Getty Museum, which generously supported her continued involvement in the aulos project. Altogether, we convened for six more study sessions at the Museum of Fine Arts from 2019–2024, being greatly supported by our colleagues there, who patiently squeezed our various requests and not least the mandatory supervision of our movements into already tight schedules.³⁶

32. Gänsicke and Hagel 2017.

33. Hagel 2019.

34. <https://www.mfa.org/exhibitions/nubia>.

35. *Ancient Music Beyond Hellenisation*, ERC Advanced Grant 787522.

36. Warmest thanks are due to Lawrence Berman, Bobby Giglio, Abby Hykin, Jayme Kurland Moran, Darcy Kuronen, Stacey Leonard, and Phoebe Segal.



Figure 3.6: Experimental configuration of items with narrow tubing, laid out along a grid of ancient semitones between rulers raised to the top plane for photographic measurements. Photograph © Stefan Hagel.

A find like this also required new software. Above all, it is next to impossible to become familiar enough with a hundred or so items of immediate musical importance and many more of potential significance, at least not when two-week-long sessions with them are interrupted by months or years of remote work with photos, figures, and sketches. Consequently we needed, in addition to the existing software for musically modeling the instruments on the basis of fundamental measurements, a database where we could collect all available information on each item and link to particular regions on all kinds of images, from the excavation photographs to the available radiographic documentation and our own material, including photos from which precise measurements could be taken (fig. 3.6).³⁷ This was realized as an online database, accessed through a specially designed desktop application (fig. 3.7).

Originally, we tried to identify individual pieces by the box in which they had resided and a number, placing a label next to each in their new trays (see ch. 4). That worked out when they were staying there or being inspected individually, but turned into a nightmare when it came to moving many items around on the table in order to determine possible configurations, even though Olga gave her best admonishing the experimenter and chasing down orphaned pieces. Eventually we realized that consistently identifying the abundant smaller items could never succeed in such a way and it would be inevitable to furnish each with a permanently attached small paper label (though easily removable with solvents). At the same time, it had dawned on us that, at least after a century of being handled and transferred, the placement of a particular piece in a particular box held hardly any useful information. After all, the components of one of the longer sections that were still connected in the excavation photographs had meanwhile ended up in three different boxes.³⁸ Therefore, while keeping the old system noted in the database, we decided to replace it with simple numbers for daily reference, which also minimized the size of the 228 tiny labels that Susanne eventually attached, generally at hidden spots (see fig. 3.8). This relatively simple measure greatly streamlined our workflows and also cleared the way for major upgrades of the evaluation software.

Once we had obtained a general overview on diverse options of fragment placement and pipe reconstruction, the decisions between these necessitated assessing their musical corollaries with greater

37. See Hagel 2012b.

38. Of compound 001+095+071+099, item 001 had come to reside in box 1; 095 and 099, in box 12; and 71, in box 10.

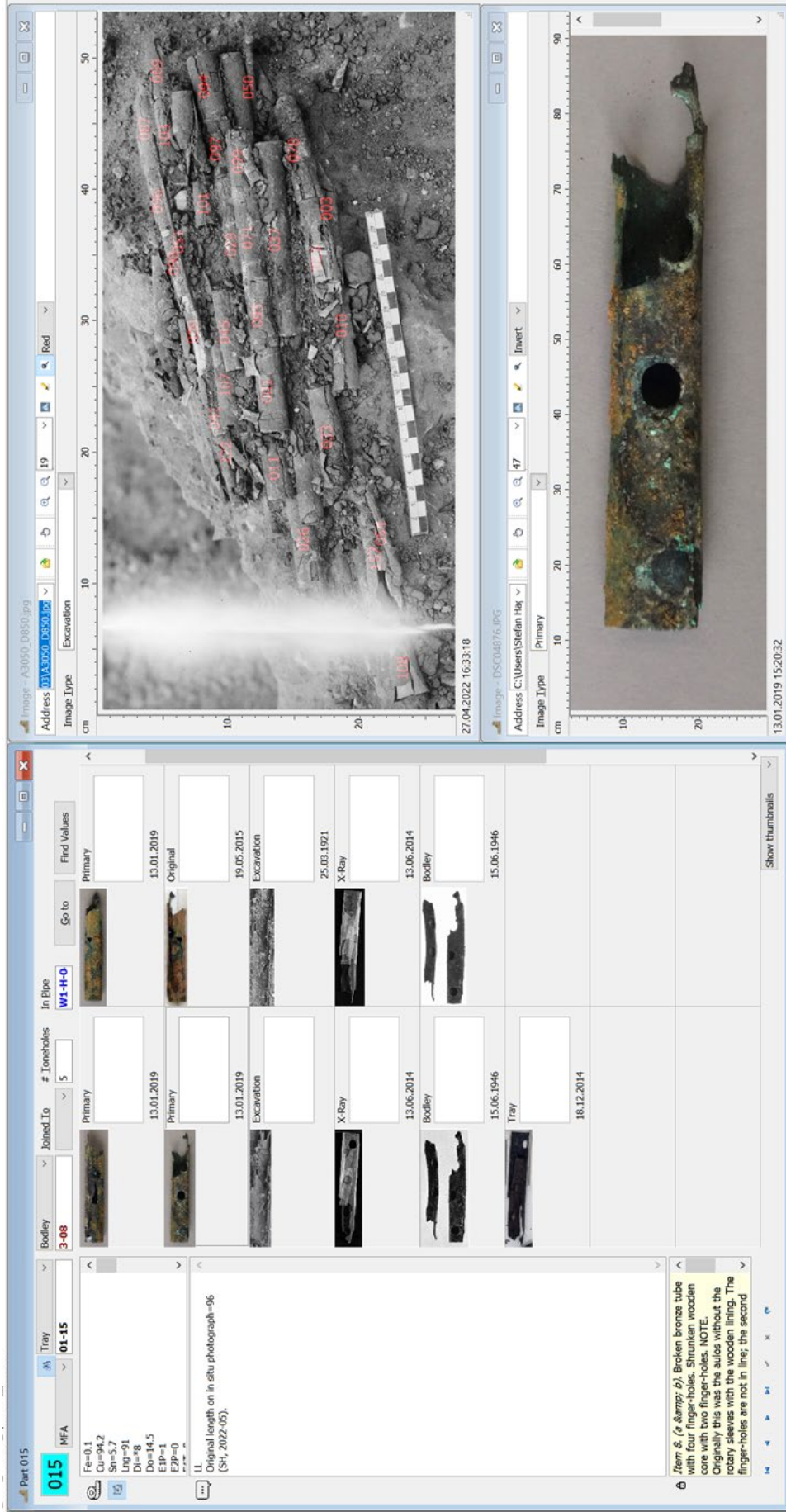


Figure 3.7: Database interface designed for the project. Left: record of item 015 with measurements, linked image regions, and quotations from Bodley 1946. Right below: linked image opened in graphics viewer. Right above: excavation photograph with superimposed IDs of linked items.

confidence and precision than could be achieved by the means described above that involved a semitone-grid sheet and rules of thumb. However, the precious working hours in the museum would have been wasted on transferring multiple potential pipe designs to the computer for evaluation. With many other tasks in addition, such as updating the records, even the nights in between would hardly have sufficed. Anyway, the processes of physical puzzling and musical evaluation were closely intertwined because to develop new design hypotheses we needed to handle the pieces and to test the musical implications of different designs with the help of the software. As a remedy, I designed a graphical interface that allowed moving sketches—or, alternatively, images—of the parts around on the screen parallel to moving the respective items on the table and watching the musical implications of every change in real time (fig. 3.9). Harmonically implausible configurations could thus be quickly excluded, so that the process eventually honed in on the solutions that will be proposed in chapter 7.

While working on a corpus so large that it would be next to impossible to keep all potentially relevant data in memory, I increasingly felt the need for quick visualization of various aspects within possible configurations. In the special case of knob shapes, this was simply achieved by displaying symbolic renditions next to the tubes. Other parameters could beneficially be visualized by coloring the pieces on the screen. In such a way, color brightness could for instance indicate internal diameters, which helped identifying reconstruction options that involve unlikely divergences within individual bores.

Teardrop-shaped fingerholes posed another challenge, as these needed to be evaluated in different degrees of openness. While definite values can be calculated only for fully open holes, an assessment of the hole without the tapering part and with various grades of covering allowed better judging possible musical uses. As will become clear below, in certain instances it also became necessary to inspect the musical effects of cross-fingering only a particular fingerhole; consequently means for emulating not only various preset configurations of open and closed holes, but also flexible cross-fingering needed to be developed. An even greater challenge represented those pipes of nonuniform bore, where new corrections needed to be applied to the formulas. This includes interpolating the lost diameters of pieces whose core has perished—a hardly satisfactory method of dealing with just another set of unknown variables, but obviously the best we can do. The presence of whole sets of pipes further suggested expanding existing algorithms for harmonicity evaluation and automated searches for optimal mouthpiece sizes beyond pairs of pipes—a task that required carefully streamlined coding in order to avoid excessive running times.

A couple of new tools also facilitated taking measurements from images. On the one hand, a viewer was included in the database front end that permitted measuring distances directly after defining a reference distance. This was particularly valuable when dealing with the excavation photographs, where lost dimensions could thus be gauged from adjacent surviving parts. On the other hand, semitransparent renditions of parts, created from the measurements that had been entered in the database, enabled checking these by overlaying photographs with the sketches, which can be scaled and rotated at will (fig. 3.10). This once more reduced a task that had formerly involved a lot of manual labor, transferring exported sketches along with selected images to some other software, to a procedure that takes less than a minute. In addition, once hypothetical restorations had been developed, the original parts including their joints were compared directly with sketches created by the software and printed to scale.

All these activities, supported by specifically developed tools and methods and including measuring, scrutinizing old photographs, physical and musical puzzle games, evaluation, and attempts at disproving hypotheses, continued during and between research visits that extended until 2024, with a significant interruption caused by the COVID pandemic. Thanks to their heuristic combinations, our understanding of the instruments improved in a virtuous cycle that now encourages us to present our conclusions to a wider public with this publication. Is this a final point? Hardly so: as long as the last bronze fragment has not found its place, we may still be in for further surprises. But the remaining material has dwindled dramatically. It might hardly suffice for filling the gaps in the existing pieces, leaving little chance that



Figure 3.8: A label attached to the bottom side of “chimney” 149. Photograph © Susanne Gänsicke.

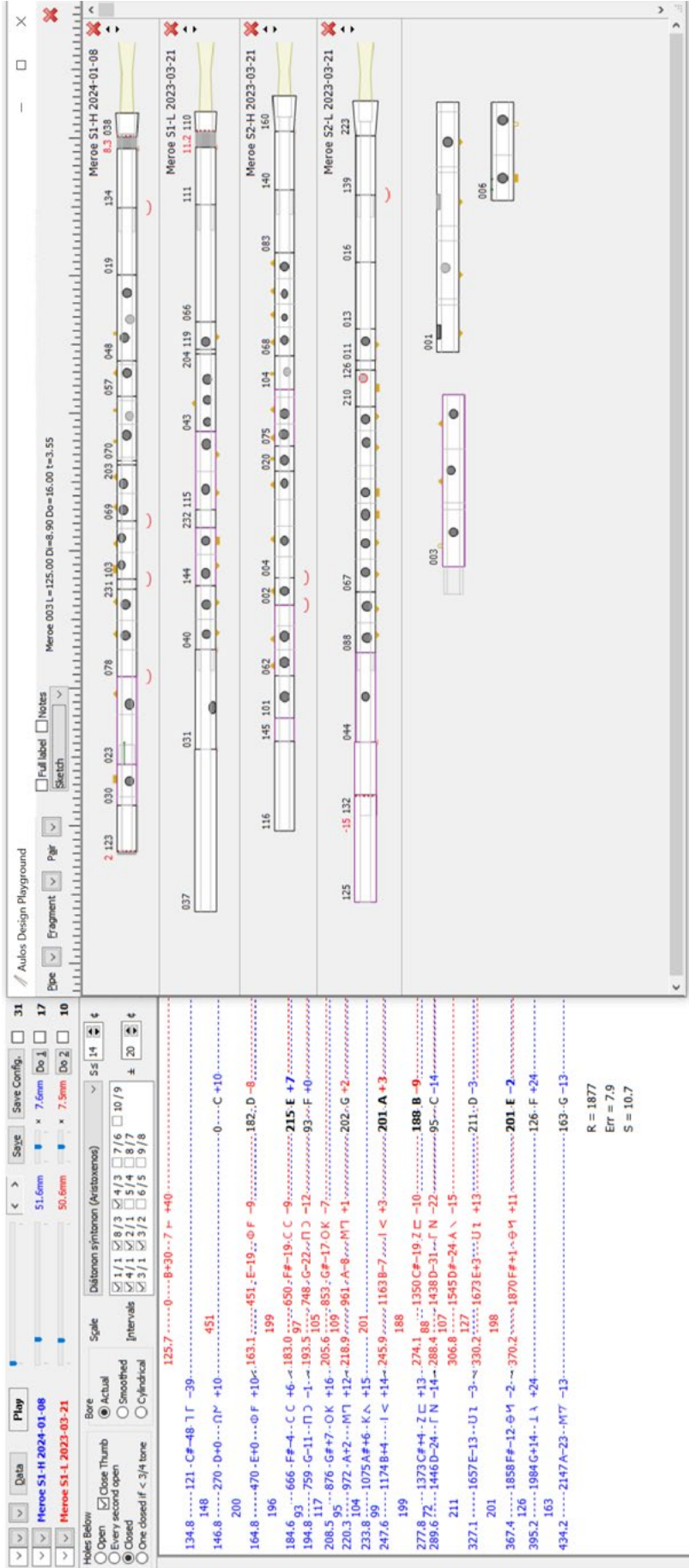


Figure 3.9: Graphical interface for evaluating possible configurations. Red brackets: fixed joints established from the excavation photographs.

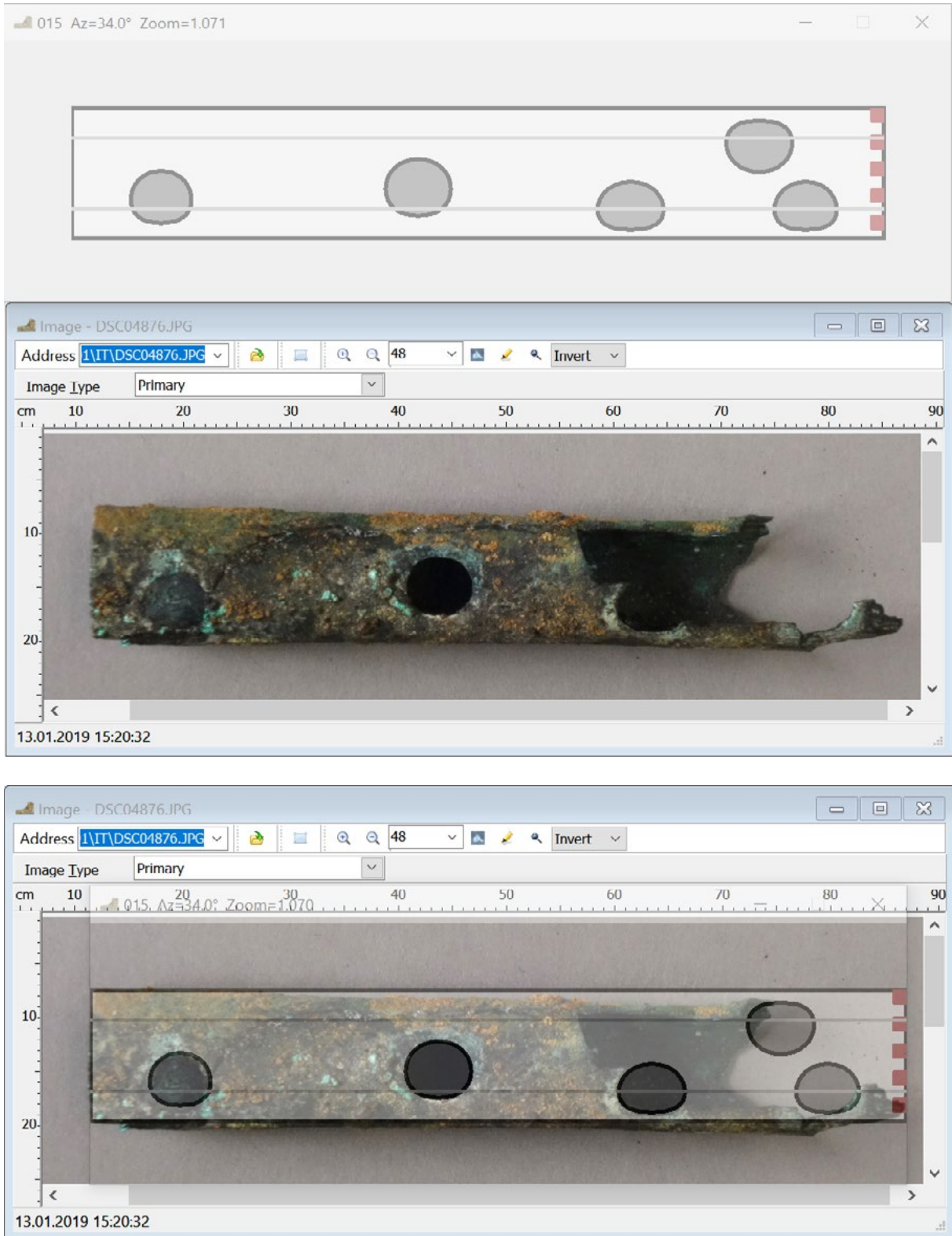


Figure 3.10: Checking relative measurements by an overlaid semitransparent model.

substantial parts escape us (unless these would already have escaped interment two millennia ago). We therefore express some confidence that not all the conclusions presented below are ill founded.

4 Conservation

Susanne Gänsicke

4.1. Introduction

In July 2013, the Departments of Musical Instruments, Art of the Ancient World, and Conservation and Collections Management of the Museum of Fine Arts, Boston (MFA) launched a collaborative conservation and interpretation project focused on a rare group of ancient reed pipes or auloi, excavated in 1921 at Meroë, Sudan, and now in the museum's collection. This marked the beginning of the now twelve-year-long process that comprised the study, examination, conservation and interpretation of these extraordinary objects, which had never before been treated or repaired by any measure. The first year was funded by the Visiting Committee of Musical Instruments. The two following years were supported jointly by the three Visiting Committees of the above-mentioned departments. My work at the MFA continued until June 2016. After July 2016 with my appointment as Head of Antiquities Conservation at the J. Paul Getty Museum, my involvement in the project continued intermittently until its completion, which is marked by this publication.

Even though the importance of this cache had long been recognized, no comprehensive interpretation was feasible prior to conservation of the highly fragmented materials. Deterioration and degradation due to the circumstances of burial, subsequent shipping, and handling caused significant alteration and loss to the original shapes and materials. By 2013, the primary image of the Meroë auloi (fig. 4.1), used on the MFA's webpage and in numerous publications, consisted of an arrangement of a selection of better preserved and more interesting sections and elements.¹ Their position did not represent an actual instrument, but merely a selective inventory of different items of what would eventually become part of twelve individual pipes.



Figure 4.1. This photograph of a selection of well-preserved auloi parts served as the primary image for the cache until 2024. 50 B.C.–1 A.D. Bronze, bone, wood. Harvard University—Boston Museum of Fine Arts Expedition. SC 65062. Photograph © Museum of Fine Arts, Boston.

The true nature of the cache was far more complicated, and depressing, and not widely known. As discussed in chapter 3, Nicholas Bodley was the first scholar to examine these auloi and published his findings in 1946. He did not attempt any physical repairs; in fact, he talked about “the impossibility of positive restoration” and remarked that “the condition of various parts of the Meroë auloi is such that a

1. The color photograph SC 65062 provided the primary image for the Auloi of Meroë for MFA publications and on its website over many years, see Kuronen 2004, 61. Doxey 2018, 152–53. The entire cache was registered as 24.1821 in the MFA collections until the end of the project, when new numbers were assigned to individual pipes.

1921
 (1) NXXX
 Thu. Mar. 22. p. 253.
 Beg. III

Remove the filling from NXXX. A and B. Among the large plates in A, two large shells, some pottery, etc. Of the large plates, two fair ones left standing, rest in the same.

(2) NXXX
 Thu. Mar. 22. p. 253.
 Beg. III

Bleeding from B in NXXX. Very little, some small bits mixed with clay, with etc. Some pottery, and a pile of shells (of shells) above in one cleaning, some from pyramid.

(3) NLI
 Thu. Mar. 22.

Continue cleaning out chamber of NLI. Let the very thickening to fall, as within the pyg one, what in the lot. A large fragment of the very fall.

(4) SVL
 Thu. Mar. 22.

cleaning up debris from A and staining, unfinished.

Wednesday, March 23, 1921
 Friday - 164.
 Work on (1) NVI.
 (2) NLI.
 (3) NXLV.
 (4) NXLIV.
 (5) NXLIII.
 (6) NXXX.

(7) NLI
 Mar. 23. Wed.

Continue cleaning staining NLI with two pyg - one in original filling from ~~the~~ of stain, the other in the same hole. The original filling is very mixed and includes surface debris, and with etc. There are yet no steps, but a ~~slight~~ do not to the original filling, what a note on the floor and 7-8 notes from ~~the~~, found a number of from other clean in large plates. These have holes and may be a plate (or thin ls).

(8) NLI
 March 23, Wed.

Continue cleaning and bleed from NLI and staining same A. It appears to have plate like N I V II.

1921
 (9) SVL
 Thu. Mar. 23. p. 255.
 Beg. III

cleaned out chamber of SVL. Beads.

(10) SVL
 Thu. Mar. 23.

Remove remains of chamber in SVL, and begin cleaning chamber. Beads are pyg. 7 fair. Others.

Thursday, March 24, 1921.
 Friday - 179.
 Work on (1) NVI.
 (2) NLI.
 (3) NXL.
 (4) NXLV.
 (5) NXLIII.
 (6) NXXX.
 (7) NXLII.
 (8) NXL.

(9) NLI
 Thu. Mar. 24.

Continued in staining of SVL with two groups as usual. Came on a bunch of "plate" (B) about a meter or so further on. Plate and couple notes. Appears to be made in section (Comp. cutting now here as has taken).

(10) NLI
 Thu. Mar. 24.


Begin cleaning ground in front of NLI, ready for stain.

(11) NLI
 Thu. Mar. 24.

Continue cleaning NLI. A. Cleaning about 30m (front of plate) out in the rock as at B. In the "thinner" debris found a number of pottery, then with ~~the~~ in head in A. Also the quite part for a large fragment of B. (two ranges).

1921
 (12) SVL
 Thu. Mar. 24. p. 256.
 Beg. III

cleaned floor of chamber of SVL. The in block is left in place as we enter one or through the thin hole.



Finish chamber of SVL.

Beads, pyg. 2m, pale feet, very and part of - fair. plagues with marks as caption.

(13) SVL
 Thu. Mar. 24.

Begin cleaning chamber of SVL. Beads, pyg. 2m, etc.

Friday, March 25, 1921
 Friday - 170.
 Work on (1) NVI.
 (2) NLI.
 (3) NXL.
 (4) NXLV.
 (5) NXLIII.
 (6) NXXX.
 (7) NXLII.
 (8) NXL.

(9) NLI
 Fri. Mar. 25.

Work on the thinner hole, well it got to account of plate, & standing the hole of plate (about 10). Remove them late in staining. (System and story)

(10) NLI
 Fri. Mar. 25.

Expand end of stain of NLI in side not to see it with debris and by - cleaning among the common pile of rubbish away, chapel of NLI.

(11) NLI
 Fri. Mar. 25.

cleaning part of NLI. Also found staining, and exposed 11 pyg. Then work below this and the front of the chapel appears to be covered in. Fair, etc. in surface debris.

Figure 4.2. Pages of the H.U.M.F.A Expedition diary with notes about the discovery of the pipes. SC 491355, SC 491356, SC 411357. Photograph © Museum of Fine Arts, Boston.

complete restoration, even of a single instrument, is not possible.”² Although Maurice Byrne provided a slightly more hopeful evaluation (see ch. 3), it is under these generally dire predictions that the actual work on the conservation project of the Auloi of Meroë began in the fall of 2013.³

At the beginning of the project, we could not anticipate the journey that lay ahead. The cache is unique in size, variety, and complexity of the instruments. Technical details to be observed, differences and similarities to instruments found in other parts of the ancient world would likely contribute to entirely new insights on ancient auloi and their comparative studies. Might we glean patterns of technologies, of raw materials used, and would any of this information imply where instruments may have been made, or lead us to learn more about the craft of the instrument maker? Documentation, technical study, and conservation were the first steps to provide information that might help music archaeologists to answer these questions and would lay the foundation for the musicological interpretation (see ch. 7).

This chapter will provide an overview on the approach in the conservation laboratory, of considerations and individual steps taken, and how the highly fragmented sections began to take shape to form actual instruments.⁴ Work was done in close consultation with the conservation scientists (see ch. 6 for technical examination), and with curators in the Department of Musical Instruments, Bobby Giglio, Jayme Kurland, Darcy Kuronen, and with the curators of Art of the Ancient World, Lawrence Berman, Denise Doxey, and Rita Freed, and with the project partners Stefan Hagel, Peter Holmes, and Olga Sutkowska.

4.2. Between 1921 and 2013

The conservation project began with a comprehensive review of all available records pertaining to their excavation, transport, and ensuing observations. The exact circumstances of the excavation of pyramid Beg. N 6 at Meroë, Sudan, and the retrieval of this cache remain largely unknown. The Harvard University–Museum of Fine Expedition (HU–MFA) Diary entry by G. A. Reisner and Ashton Sanborn of March 23, 1921, nonetheless, allows glimpses into the discovery (fig. 4.2):

“...found a number of bone tubes cased in bronze plate. These have holes and may have been a flute (or similar),”⁵

followed by March 24, 1921

“... came on a bunch of “flutes” (?) about a meter or so further on. Photo and careful notes. Appear to be made in sections (bronze casing over reed or bone tubes).”⁶

The last excavation entry of March 25, 1921, adds further scant information

“... recording the bunch of flutes (about 18). Removed them late in the day (Sanborn and Story).”⁷

The HU–MFA Expedition Object Register of March 23–25, 1921, provides two excavation numbers for the cache: 21–3–350, and 21–3–702. The entry of March 23, 1921, states:

“21-3-350 ... fragments of a flute, pipe of bronze, with mouthpiece of bone. original filling in stairs.”⁸

2. Bodley 1946, 218.

3. At that time, I served as Conservator in Objects Conservation at the MFA.

4. For a blog on the project see also <https://www.mfa.org/collections/conservation/featured-projects/auloi-of-meroe>.

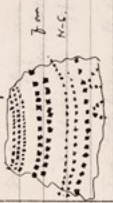
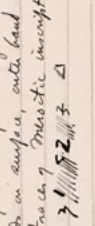

5. Harvard University–Museum of Fine Arts, Expedition Diary 1920–21, 253. The term “flutes” used by Reisner (and others) in connection with the Meroë auloi is incorrect.

6. Harvard University–Museum of Fine Arts, Expedition Diary 1920–21, 255.

7. Ashton Sanborn and Hanford Lyman Story. Harvard University–Museum of Fine Arts, Expedition Diary 1920–21, 256.

8. Harvard University–Museum of Fine Arts Expedition, Object Register IX, Begarawiyeh (Meroë), 238.

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No.	DESCRIPTION	MATERIAL	MEAS.	DATE	PROVENANCE	REMARKS
21-332	Fragment of a plate, 1/2 in. g. high, most mouth piece of bowl.	Orange + brown	1 1/2 in. diam. x 1/2 in. high	24 Mar.	N. VI. Egyptian	
21-333	A few small sp. of a jar, black ware; impressed design.	Black				
21-334	Fragment from rim of a large coarse red ware tray? (Made on a dirt floor, as indicated by rough bottom)	Red ware	10 cm. diam.		S. X 1 X Thiers, debris in front of den	
21-335	5 ft. from jar, common coarse red ware, red ware outside?					
21-336	3-4 greenish grey frit plaques? (a) - purple green glaze, shows 5 parallel flat bands on surface, outer band has traces of hieroglyphic inscription	Frit	1 1/2 in. x 1 1/2 in.			
21-337	Small frag. pink-yellow body, yellow glaze; feather? alternate pink black	Frit	1 1/2 in. x 1 1/2 in.			
21-338	Black, 220 green bag parts 15 yellow, yellow glaze	Black	1 1/2 in. x 1 1/2 in.			

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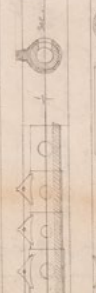

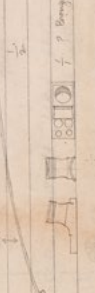

No.	DESCRIPTION	MATERIAL	MEAS.	DATE	PROVENANCE	REMARKS
21-302	Many fragments of at least five (probably 5) flat-like animal instruments. Straight tubes of very coarse brown mud. Sections: with sand and all over. Color: reddish brown, slip and pits. Length not obtainable, but cannot be less than ca. 45 cm. Jointed sections presumed to be 13-1. (Appear to be large and small (4) two and pieces of different diameters).	Orange + brown	See text	1921	Preparatory	
						
						
						
						
						

Figure 4.3. Two pages of the H.U.M.F.A Expedition object register, one with sketches of a few interesting sections, such as a dolphin, knobs, chimney, and turning tubes. SC 491359, SC 491358. Photograph © Museum of Fine Arts, Boston.

A second longer entry, dated March 23–25, 1921, provides small sketches of the more complex and interesting sections of the instruments (figures 4.3.1–2) and the following text entry

“21-3-702.... Many fragments of at least four (probably five) flute like musical instruments. Straight tubes of ivory encased in bronze, made in sections, with round and oblong holes, mouthpieces, tops, and fittings. Length not obtainable but cannot be less than ca. 45 cm. Jointed section preserved of ... B.L. Appear to be large and small (... two end pieces of different diameters)”.⁹

Unfortunately, no information is available about the circumstances of how the find was retrieved from the soil. Due to the size of the complex, the degradation of their materials, the pipes must have been very brittle and difficult to handle.

The expedition packing list of 1924 (fig. 4.4) also provides little information that helps us to understand the process of packing for the long transport to Boston: “August–September, 1924. LIST A: Cases marked M.F.A. p. 3 A#. BM 267:, BMS 268: (*musical*) wood, bronze, ivory, from...; BMS 269 Beg. N. VI (No. 21-3-703).¹⁰

In the excavation publications the find was described as

“Group of musical instruments of ivory encased in bronze, representing at least 9 and possibly 12 or more auloi. In situ Pl. LIX A (as first exposed) and Pl. LIX B (after removal of top layer)”.¹¹

The two plates provide the most important and interesting points of reference for the pipes in two high-resolution excavation photographs, which were taken in situ.¹² One image (fig. 4.5) shows the cache when first exposed; its negative now exhibits a damaged section on the left side, which results in irretrievable loss of information on the pipe arrangement as found. The second image (fig. 4.6) shows the cluster in a wider angle and after several pipes had been removed.

The combination of notes and visuals from the excavation and ensuing publications illuminate the confusion of the excavators and scholars when encountering this find. The excavation diary mentions there may have been as many as eighteen pipes.¹³ Since then, this number has not been further substantiated by other descriptions nor our own work. Yet, it is astounding that the estimated number of pipes in the 1957 excavation publication “*at least 9 and possibly 12 or more auloi*” is close to the results of our current project and illustrates how much more readable the fragments may have been decades ago and what terrible trauma they experienced since then.

A second, far smaller number of remarkably similar aulos fragments had been excavated at the Royal City of Meroë by John Garstang between 1909–1914.¹⁴ They were kept in the Museum of the Institute of Archaeology at the University of Liverpool, but their presence could not be verified more recently and unfortunately, they could not serve as comparanda for our work (see ch. 8).¹⁵

The fragmented instruments were housed at the MFA in fourteen wooden trays until the beginning of the conservation project. There were ten shallow, almost square trays and four longer and deeper ones. The deeper ones were padded with unprocessed cotton wool, covered by undyed cotton textile. Interspersed between the fragments were small pieces of paper with notes from the excavators, some written in Arabic, and from Maurice Byrne. It appears reasonable to assume that the trays were created in the Sudan after excavation, that the objects were placed into them at Meroë, and that they were shipped

9. Harvard University–Museum of Fine Arts Expedition, Object Register IX, Begarawiyeh (Meroë), 302. It is important to note that both bone and ivory are terms used, based on visual criteria only.

10. Harvard University–Museum of Fine Arts, Packing list: August–September, 1924. LIST A: Cases marked M.F.A. p. 3 A#: “2) BM 63 contains five small boxes,– a) BMS 267: – all three contain the broken flutes.....”.

11. Dunham 1957, 109.

12. Dunham 1957, pl. LIX A, B.

13. G. A. Reisner and Ashton Sanborn, Harvard University–Museum of Fine Arts, Expedition Diary. Vol. X. Sudan, Part 6, Begarawiya (Meroë) 1920–21, 256.

14. These fragments were never mentioned by Garstang in his publication on excavations at Meroë.

15. Southgate 1915; <https://garstangmuseum.wordpress.com/2020/04/28/meroe-africas-forgotten-empire/>.

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PACKING LIST: Autust-September, 1924. LIST A: Cases marked M.F.A. p.3. A3
Brought forward 13,391

No.:	CONTENTS:-	
MFA 232...	Five sugar boxes,-Nos.262,263,264,265, and 266:-	266
1001)	Box BM 262 contains three small boxes,-	
30	a) <u>BMS 264</u> :-ivory box-inlays from Begarawiyah.....	
	see Sheet C/10	
13	b) <u>BMS 265</u> :-misc.unimportant frags' from Beg.....	
	see Sheet C/10.	
58	c) <u>BMS 266</u> :-misc. small objects from Barkal and Beg...	
	see Sheet C/10.	
372)	BM 263 contains five small boxes,-	
5	a) <u>BMS 267</u> :-all three contain the broken flutes.....	
5	b) <u>BMS 268</u> :- (musical) wood, bronze, ivory, from.....	
5	c) <u>BMS 269</u> :-Beg. N.VI (No.21-3-702).....	
10	d) <u>BMS 270</u> :-arrow-heads of bone, stone, bronze, iron	
	from Beg. W 122.....	
	see Sheet C/10.	
13	e) <u>BMS 271</u> :-beads, amulets, and fragments misc.	
37	24 entries from Beg. and Barkal.....	
	see Sheet C/10.	
313)	BM 264 contains three small boxes,-	
10	a) <u>BMS 272</u> :-pottery, etc. from Barkal.....	
	see Sheet C/11.	
14	b) <u>BMS 273</u> :-vessels glass and silver,-four from Beg....	
	see Sheet C/11.	
7	c) <u>BMS 274</u> :-frags. glass, fai., bronze, barkal and Beg..	
31	see Sheet C/11.	
204)	BM 265 contains misc. pottery and potsherds from	
	Gebel Barkal and Begarawiyah.....	
785)	BM 266 contains three small boxes,-	
366	56a) <u>BMS 275</u> :-bottom of boxed wood, carved, Barkal; 20	
	frag. fai. plaque relief, Barkal; 5	
	3 gold necklace elements, Beg. N XVI; 15	
	bronze key, Beg. N XVI; 1	
20	b) <u>BMS 276</u> :-misc. small objects from Beg. and Barkal. 56.	
	misc. small objects of bronze, fai., Beg 20...	
	for 275 and 276, see Sheet C/11.	
2	c) <u>BMS 277</u> :-one bronze bucket from. Beg. W 177..(broken) 2.	
78	see Sheet C/12.	
MFAA233...	Five sugar Boxes,-Nos.267,268,270,278, and 273:-	109
23	1) Box BM 267 contains three small boxes,	
3	a) <u>BMS 278</u> :three bronze vessels from Beg.....	
10	b) <u>BBaS 281</u> :-pottery, f.dep. Barkal Temple B 700.....	
10	c) <u>BBaS 282</u> :-pottery, f.dep. Barkal Temple B 700	
23		
26	2) Box BM 268 contains three small boxes,-	
7	a) <u>BMS 279</u> :-bronze and pottery vessels from Begarawiyah...	
9	b) <u>BMS 280</u> :-misc. beads, frags. etc. (94 entries) from Barkal, X	
	Nuri, Kur'uw, Begarawiyah.....	
10	c) <u>BMS 283</u> :-three skulls from Beg. N XVII.....	
26		
20	3) Box BM 270 contains-	
	one large amphora (pottery) from N XVIII:21-3-376 b.....	

Figure 4.4. Shipping list of objects from the H.U.M.F.A Expedition from Sudan to Boston, Sept-August 1924. SC 491354. Photograph © Museum of Fine Arts, Boston.

in them to Boston. We do not know if the excavators were able to identify individual pipes and if each tray reflects an attempt to remove one original pipe.

Important are the first photographs, taken in 1939 (see also inventory of ch. 5), of a limited number of better-preserved sections for Bodley's publication (fig. 4.7). They provide evidence of some clusters of



Figure 4.5. The first image of the auloi cache in situ in the staircase leading to the burial chamber of Queen Amanishakheto, Beg. N. 6, Meroë, Sudan. Photograph by Mohammedan Ibrahim Ibrahim, March 26 (?), 1921. Harvard University–Boston Museum of Fine Arts Expedition A3050_NS. © Museum of Fine Arts, Boston.

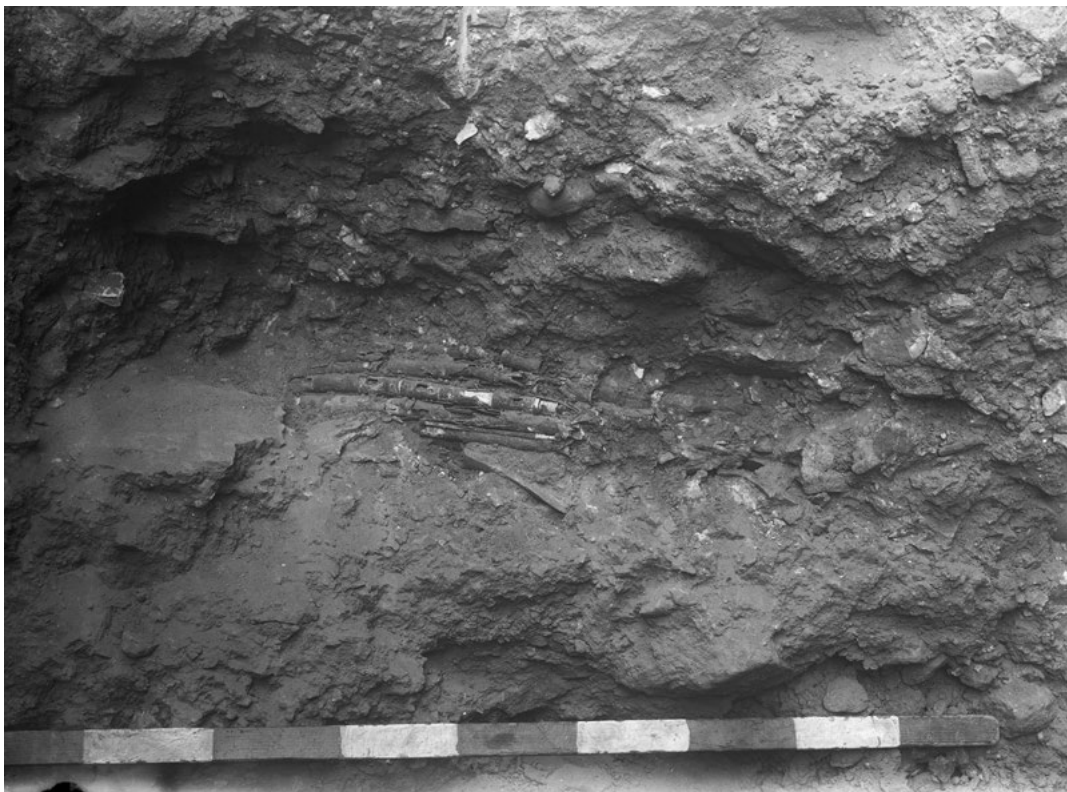


Figure 4.6. The cache in situ, second image after some pipe sections had been removed, five days after the first image was taken. Photograph by Mohammedan Ibrahim Ibrahim, March 25, 1921. Harvard University–Boston Museum of Fine Arts Expedition C9218_NS. © Museum of Fine Arts, Boston.

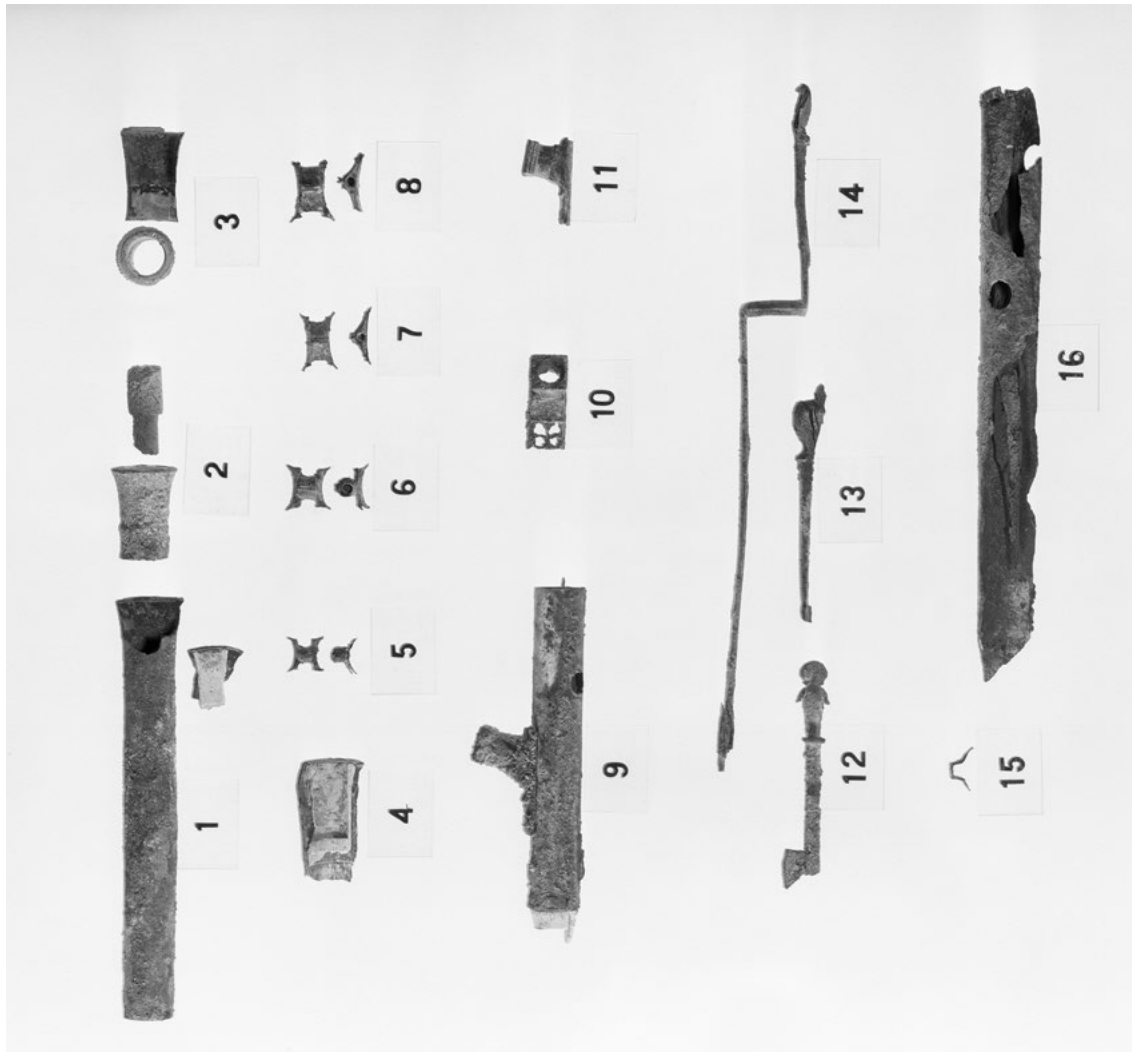
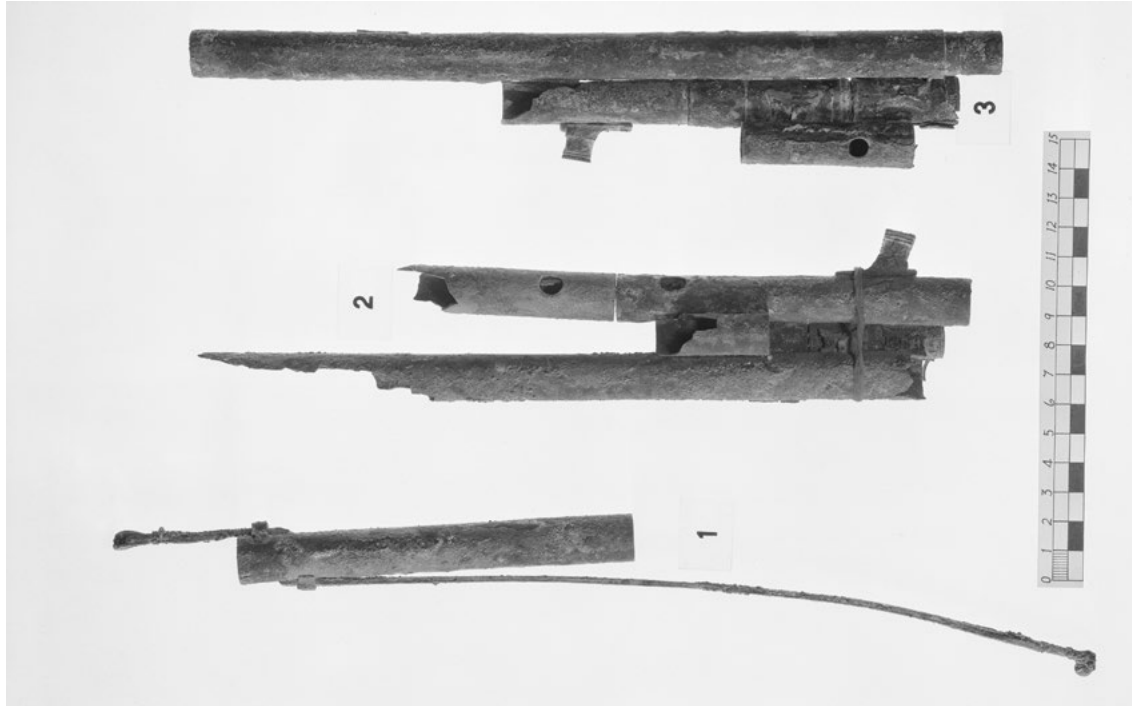


Figure 4.71–2. Photographs of auloi sections for Bodley's 1946 article (taken in 1939), which served as an initial anchor point in studying the seemingly countless sections. C 9489, C 9490. Photograph © Museum of Fine Arts, Boston.

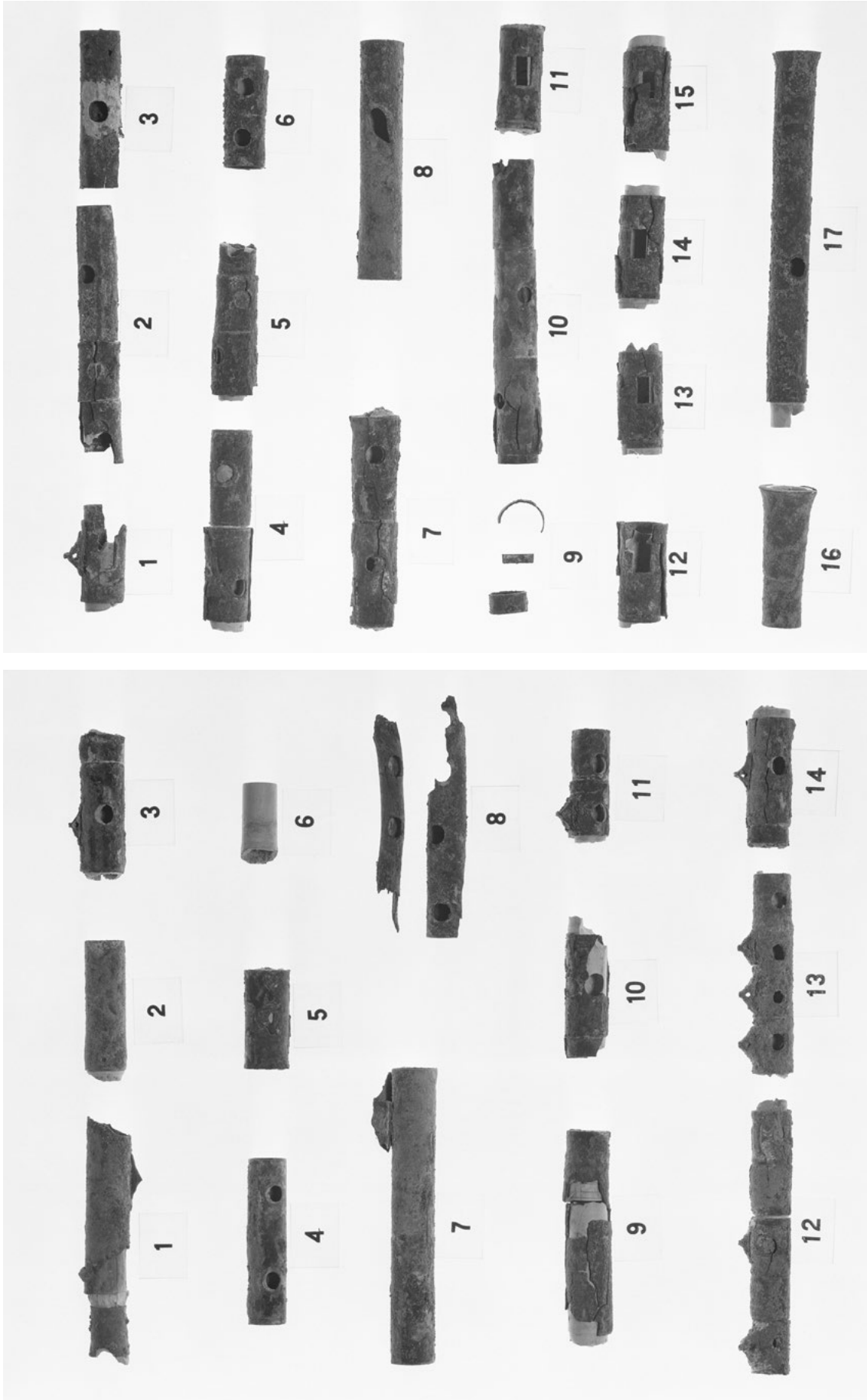


Figure 4.73–4. Photographs of auloi sections for Bodley's 1946 article (taken in 1939), which served as an initial anchor point in studying the seemingly countless sections. C 9491, C 4992. Photograph © Museum of Fine Arts, Boston.

tubes that were kept in the trays as agglomerates, being fused by corrosion products or held together with rubber bands. It is likely that their arrangement preserved their burial position, although since 1939 some have become separated, and the identification of these parts was one of our first goals.

In 1996, the trays were documented by B&W photography concurrent with Maurice Byrne's first visit to the museum (see ch. 3), see figures 4.8–4.36. Byrne examined all fourteen trays (see ch. 3, fig. 3.1); he also removed the upper layer of tray 12, and Darcy Kuronen created a new tray 12A using modern materials to lay out the sections contained in there. In 1996, no B&W image was taken of the bottom layer of tray 12 after the top layer had been removed.



Figure 4.8. Tray 1, F 3221, 1996–11–12. Photograph © Museum of Fine Arts, Boston.



Figure 4.9. Tray 1 (numbers were added on the upper edge of the fourteen wooden trays after B&W photography), SC 285259, November 2013. Photograph © Museum of Fine Arts, Boston.



Figure 4.10. Tray 2, F 3222, 1996-11-12. Photograph © Museum of Fine Arts, Boston.



Figure 4.11. Tray 2, SC 285260, November 2013. Photograph © Museum of Fine Arts, Boston.



Figure 4.12. Tray 3, F 3223, 1996-11-12. Photograph © Museum of Fine Arts, Boston.



Figure 4.13. Tray 3, SC 285261, November 2013. Photograph © Museum of Fine Arts, Boston.

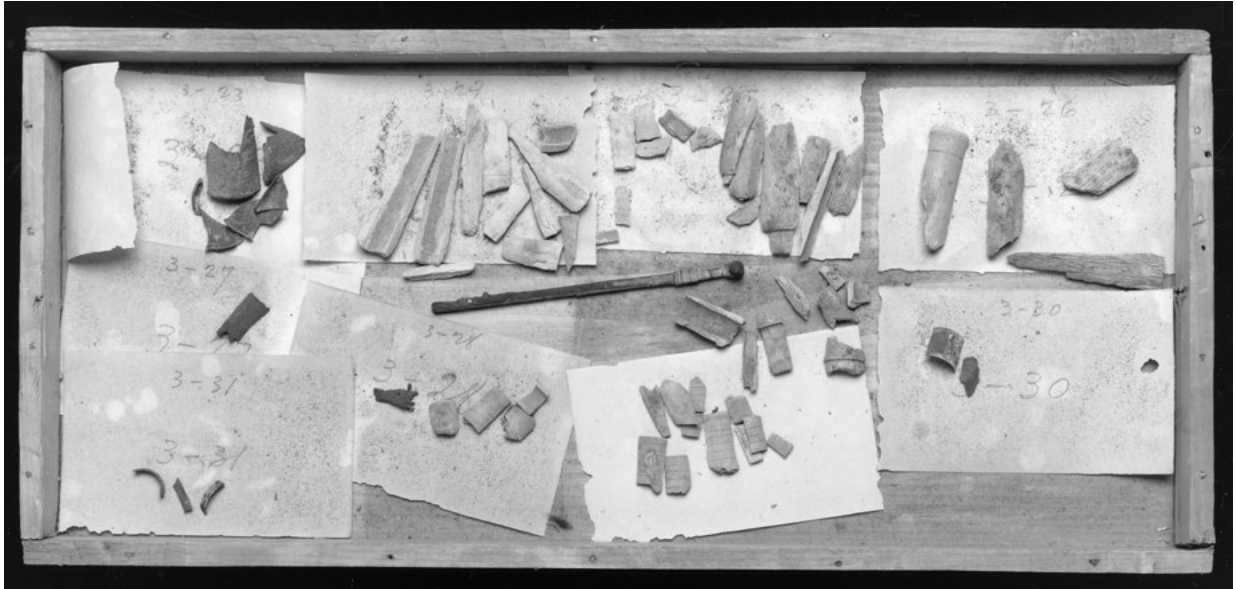


Figure 4.14. Tray 4, F 3219, 1996-11-12. Photograph © Museum of Fine Arts, Boston.



Figure 4.15. Tray 4, SC 285262, November 2013. Photograph © Museum of Fine Arts, Boston.

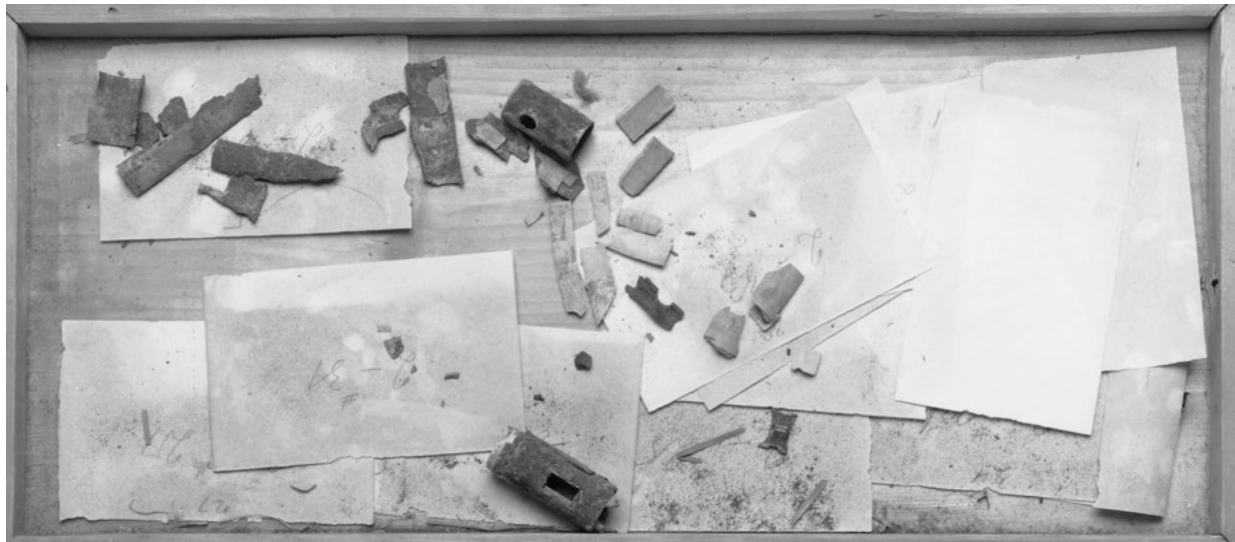


Figure 4.16. Tray 5, F 3220, 1996-11-12. Photograph © Museum of Fine Arts, Boston.



Figure 4.17. Tray 5, SC 285263, November 2013. Photograph © Museum of Fine Arts, Boston.

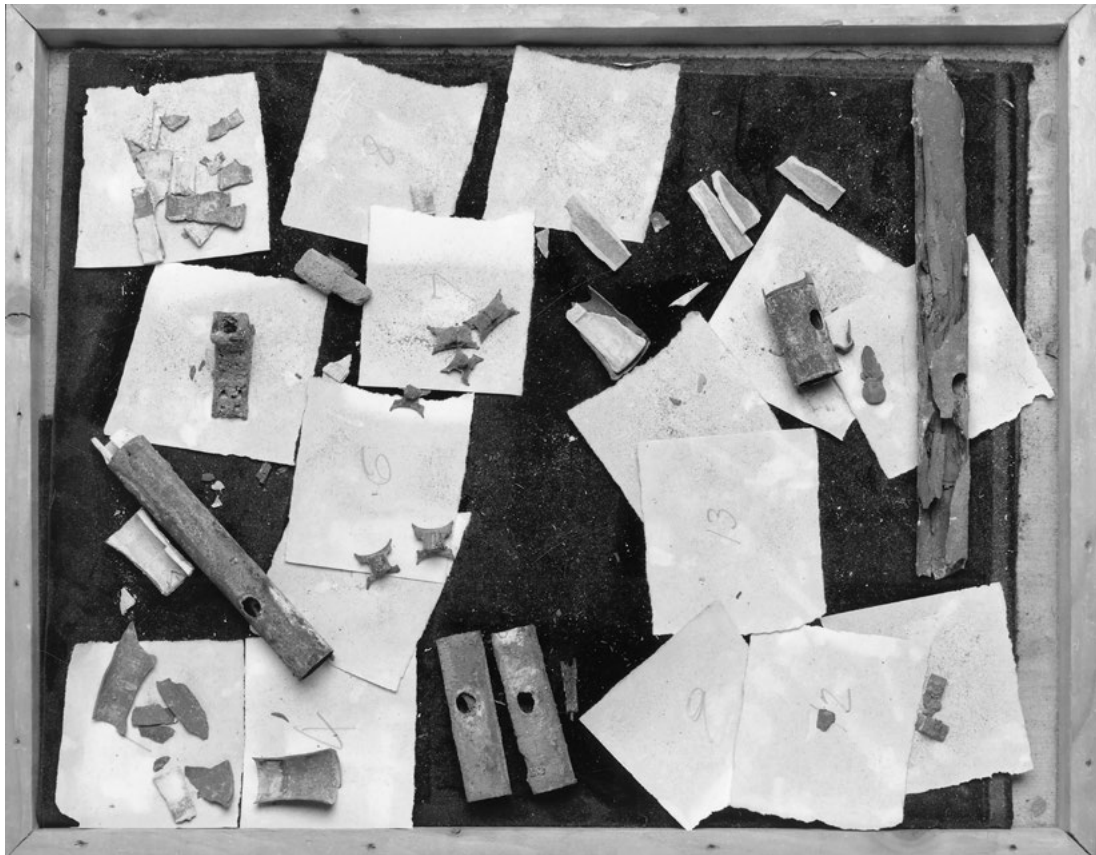


Figure 4.18. Tray 6, F 3226, 1996-11-12. Photograph © Museum of Fine Arts, Boston.



Figure 4.19. Tray 6, SC 285264, November 2013. Photograph © Museum of Fine Arts, Boston.



Figure 4.20. Tray 7, F 3228, 1996–11–12. Photograph © Museum of Fine Arts, Boston.



Figure 4.21. Tray 7, SC 285265, November 2013. Photograph © Museum of Fine Arts, Boston.



Figure 4.22. Tray 8, F 3229, 1996-11-12. Photograph © Museum of Fine Arts, Boston.

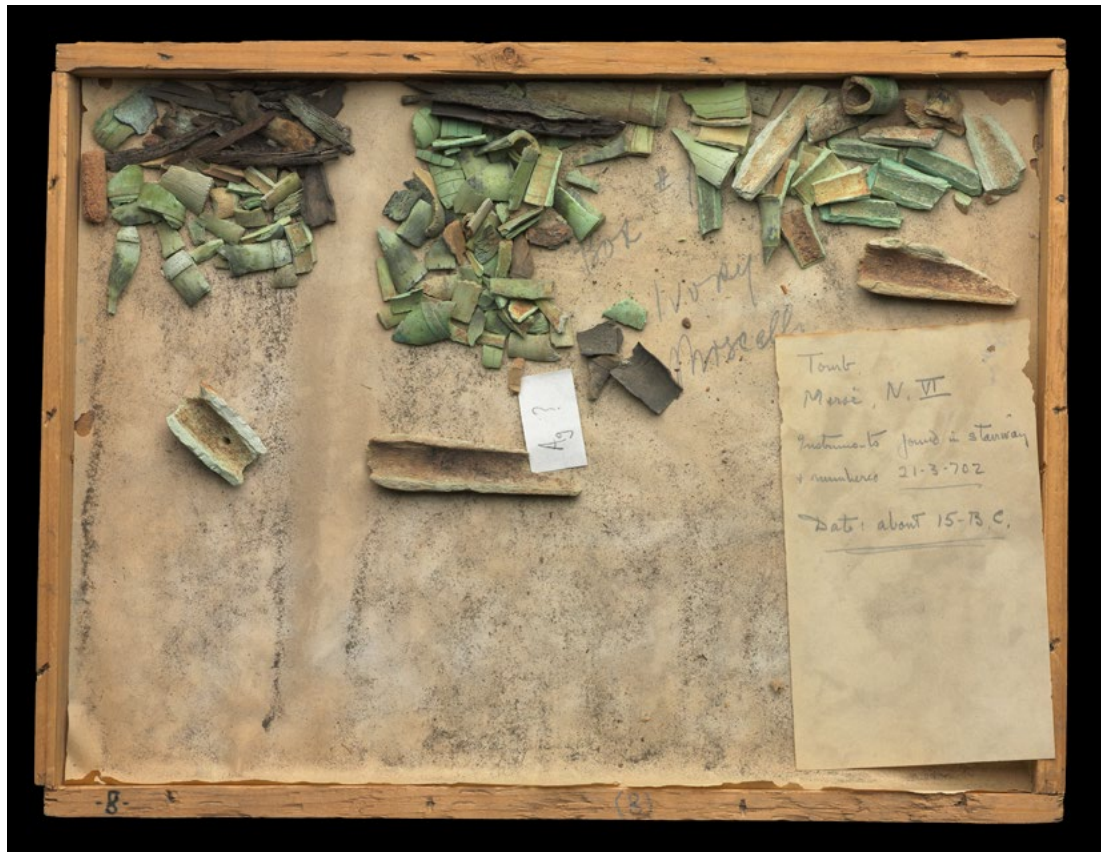


Figure 4.23. Tray 8, SC 285266, November 2013. Photograph © Museum of Fine Arts, Boston.

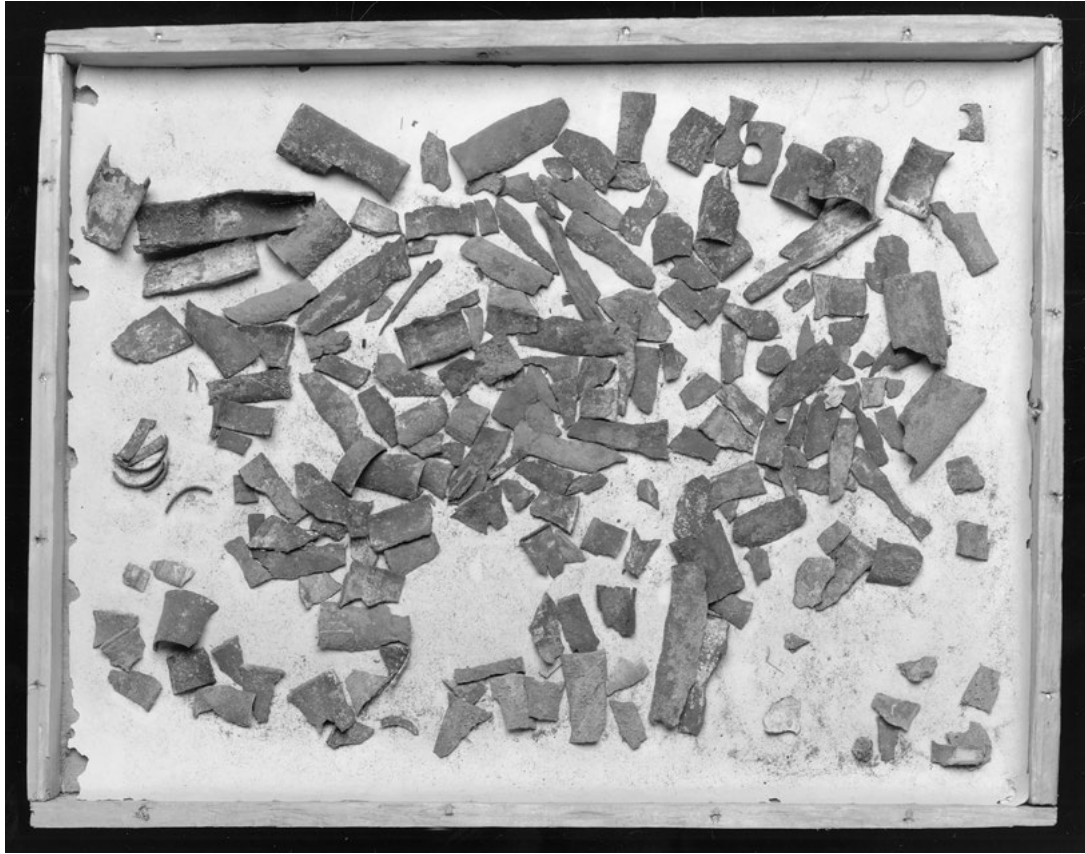


Figure 4.24. Tray 9, F 3227, 1996-11-12. Photograph © Museum of Fine Arts, Boston.



Figure 4.25. Tray 9, SC 285267, November 2013. Photograph © Museum of Fine Arts, Boston.



Figure 4.26. Tray 10, F 3230, 1996-11-12. Photograph © Museum of Fine Arts, Boston.



Figure 4.27. Tray 10, SC 285268, November 2013. Photograph © Museum of Fine Arts, Boston.



Figure 4.28. Tray 11, F 3232, 1996-11-12. Photograph © Museum of Fine Arts, Boston.



Figure 4.29. Tray 11, SC 285269, November 2013. Photograph © Museum of Fine Arts, Boston.



Figure 4.30. Tray 12, top layer, F 3231, 1996-11-12. Photograph © Museum of Fine Arts, Boston.



Figure 4.31. Items removed from top layer of tray 12 (into new tray 12A), SC 285271, November 2013. Photograph © Museum of Fine Arts, Boston.



Figure 4.32. Box 12 bottom layer in 2013 (the bottom layer was not photographed in 1996), SC 285270. November 2013. Photograph © Museum of Fine Arts, Boston.



Figure 4.33. Tray 13, F 3225, 1996-11-12. Photograph © Museum of Fine Arts, Boston.



Figure 4.34. Tray 13, SC 285272, November 2013. Photograph © Museum of Fine Arts, Boston.



Figure 4.35. Tray 14, F 3224, 1996–11–12. Photograph © Museum of Fine Arts, Boston.



Figure 4.36. Tray 14, SC 285273, November 2013. Photograph © Museum of Fine Arts, Boston.

4.3. Documentation and Rehousing

In 2013, most of the elements were still stored in the fourteen wooden trays, except for the newly created tray 12A. At the onset of the project in November 2013, the fourteen trays were recorded using high resolution digital photography to provide a baseline for documentation, see figures 4.8–4.36.

By comparing tray images from 1996 and 2013, it became clear that, in the interim, the wooden trays had been numbered 1–14 with black marks on their rims. These numbers are not apparent in the 1996 B&W images, and it remains unclear by whom and when they were created. One might suspect the numbering was done either by Maurice Byrne at one of his study visits or by an MFA staff member. Henceforth, the tray numbers served as prime identifiers (with sub numbers) for the corpus of fragments in this study until the inventory was developed (see ch. 5).

In Boston, in the nine decades since arrival of the shipment from Sudan, the pipe elements had without doubt been handled and sorted repeatedly, although no notes exist on what was done by whom, and why.¹⁶ Based on the B&W images, it appears that by the 1990s, many of the bone and bronze fragments had been sorted and separated into different trays, whereby numerous original associations were likely lost, for examples in trays 7, 8, and 9.

The old containers had likely allowed the fragments to jostle against each other during their long travel from Sudan to Boston and since their arrival in Boston almost one hundred years ago, causing further damage. The first phase of the conservation project was thus concerned with removing the fragments from the fourteen shipping containers and rehousing them in archival storage trays. Since much information about adjacencies of sections was going to be lost, it was important to record the positions of fragments in detail in an attempt to preserve their location and their association with neighboring bits. Many fragments were of similar size and although the 2013 color images provided important high-resolution documentation, the multitude of fragments were difficult to tell apart.

In the rehousing process, the individual pieces were cross-checked against earlier images, and their locations noted, to record contiguities which might prove to be useful for future reconstruction. The preliminary numbering system was based on shipping trays 1–14, adding additional sub numbers, such as 1.1, 1.2 etc. A modular system of smaller boxes in the new trays allowed constant reconfiguration to serve the needs of sections in each particular tray (fig. 4.37). Since physical connections needed to be established between fragments during this project, which would create longer individual pipe sections, this new storage system allowed flexibility for ongoing adjustment.

4.4. Condition of the Different Materials

The primary materials of the instruments, bronze, silver, lead-tin solder, bone, wood, and textile fibers survived the 2000-year burial in varying rates of preservation and deterioration. Below is a summary of conditions and patterns that were observed.

4.4.1. Bronze

By far the largest number of items were thin-walled copper alloy tubes of varying length; short tubes of just under 2 cm in length to long tubes measuring up to 27 cm and numerous thin rings. There was a plethora of additional fragments of disintegrated tubes—and an uncountable array of metal slivers.

The copper alloy exhibited various degrees of corrosion and mineralization, and the degradation was not always uniform. The nature of the material varies now from fully metallic to almost fully mineralized (see ch. 6 for analysis of corrosion samples). Several specific types of surfaces observed across many of the fragments ranged from: 1) thin matte black patina; 2) dense green corrosion compounds of varying colors; 3) dark brown warty corrosion with likely red cuprite; 4) light green pustules (likely chloride corrosion), so-called bronze disease; 5) darker turquoise-colored corrosion, mostly on the interiors of the tubes; 6) adhering orange colored sand; and surprisingly 7) also smooth metallic patches of a brassy yellow metal (likely bronze) (fig. 4.38). Interesting is the variety of patterns observed, often on a single tube section, related to the micro burial environment.

Volume increase and related cracking due to mineralization is observed on thicker parts, for example on the dolphins (fig. 4.39) and some of the sliders (but not on the three chimneys). Some distortion of tube sections is severe and appears to have been inflicted by mechanical damage before burial. Numerous broken-off bronze slivers are attached to the exterior of longer tubes; they remain securely joined by corrosion products and cannot be separated without damage.

Additional three-dimensional sections such as knobs and chimneys were better preserved than the thin tubes, perhaps not surprisingly, given the thicker material. Their cast structure was also not further

16. See also p. 31, remarks by Maurice Byrne.



Figure 4.37. Tray 8 during treatment after rehousing and sorting. The new temporary storage trays were fitted with smaller boxes of different sizes which could be modified to serve the needs to the “growing” segments (November 27, 2013). Photograph © Museum of Fine Arts, Boston.



Figure 4.38. Tube section 003 exhibiting locally a smooth metallic surface in an area where a knob was lost (2X).

deformed by cold working creating stress patterns in the metal structure, which is more readily susceptible to corrosion (see ch. 6).

The sum of these observations led to the conclusion that the materials in their current condition would impose limitations on their physical reconstruction.

4.4.2. Other Metals

Knobs, chimneys and slider holders were attached during manufacture with solder, a tin lead alloy. These solder joints often failed due to advanced corrosion of the solder. A whitish crusty residue is visible at the places where solder was used and is now nearly completely mineralized. Often a distinct pattern or imprint of a formerly attached part was recognizable and allowed the joining of fallen-off elements into their original position (fig. 4.40).



Figure 4.39. The dolphin-shaped slider end 053 exhibits advanced mineralization and cracking related due to volume increase during this process.

Some elements of the copper alloys were covered with a hazy white corrosion which might suggest the presence of tinning (see ch. 6).

Some of the bone bulbs were enveloped at their narrowest section with a thin sheet of silver (fig. 4.41). Today, only a few segments of the silver remain, now of brown color, highly mineralized and brittle, and smaller mineralized parts of the silver sleeves were found amongst other fragments.

4.4.3. Bone

The dense, light-colored organic material of tubes and their broken fragments in the cache has been variably referred to as bone or ivory in previous publications (see ch. 6 on bone identification). Different textures were observed on these pieces, from smooth and dense outer surfaces to more raw interior borings exhibiting a spongy texture indicative of trabecular or cancellous bone. Some exteriors also exhibited Haversian canals. Based on these superficial observations we will refer to this group of material as bone to the exclusion of ivory (see also ch. 6 for analysis).

These light-colored fragments formed the inner lining of the copper alloy tubes, bulbs, and reed cones, and while mostly highly fragmented, also solid bulbs and tubes have survived (see figures of trays 4.8–4.36). The most shattered elements were the reed cones due to their extreme thinness. Even though very much destroyed and splintered, many fragments would prove to be solid enough to be handled and joined. Sockets and reed cones or flares are often detailed with fine incised lines and grooves—parallel lines on sockets, thin vertical lines on the large reed cones.

The color of the bone ranged from dark white/beige to darker brown, and areas stained by metal corrosion products: many sections that were in direct contact with the copper alloy are now colored in various shades of green. The bone surface of the bulbs that were decorated with silver showed brownish stains and adhering corrosion.

Reed cone 160 contained a compact soil plug that preserved the inner stepped surface of the reed cone. Only one other soil plug (section 228) was identified in the corpus. Whether these plugs are well-preserved attributes of burial or were applied intentionally, perhaps with a binder, remains unanswered for now.



Figure 4.40. Tube section 089 with a rectangular pattern around which matches the underside of a chimney.



Figure 4.41. Bone bulbs (from top to bottom 138, 140, 139) with applied silver sleeves or traces thereof. 138 is the largest and is missing the bottom socket. 139 and 140 are almost identical in size and shape. The bottom end of 139 is inserted into a bronze tube the way it was intended to be.

4.4.4. Wood

The second material used for the inner lining of the metal tubes was wood, which is now almost exclusively separated from the metal tubes. One rare section was lined half with bone and half with wood (101, see ch. 5 inventory). The wood is now overall of a dark-brown color, very soft and powdery, extremely fragmented, and longer wood sections are distorted. The material is not only desiccated but was likely damaged by fungal decay. In a few instances, however, the wood was well enough preserved in sections with sound holes and other features (see ch. 6), which provide important information on the pipe construction.

4.4.5. Fibers

Upon closer examination it became evident that also textile fibers are preserved on the pipes in two specific locations: on bone sockets and, as twisted fibers, close to the metal knobs on the pipe exteriors, as well as in small holes of the knobs. These materials appeared to be preserved in their original matter, rather than as pseudomorphs (see ch 6).

4.5. Conservation

From late 2013 until May 2015, the initial phase of the project involved documentation, rehousing, examination, sorting, and, ultimately, joining fragments. The mandate during this period was to prepare the seemingly infinite number of fragments for evaluation by music archaeologists who would join the project in 2015, as the physical nature of the instruments could not be fully evaluated by examining the fragments in their scattered state (see ch. 3). It was thus essential to recreate sections by identifying joints and adjacencies and to reconstruct as many tube sections as possible to facilitate further interpretation.

Despite the less-than-ideal retrieval of the pipes from the ground, the excavators did not impregnate the fragments with wax or other materials typically used during excavations at the time. Before the project began in 2013, no attempts were made to clean the fragments, join them with adhesive, or preserve or alter the pieces in any way. In summary, while we were working with greatly degraded materials, they were uncontaminated and untouched by recent interventions—in other words, ancient, virgin matter. Given these circumstances, the conservation approach to this extremely fragmented complex of musical instruments had to consider several important factors.

The primary treatment goal was to physically assemble the broken pipes as much as possible and to reconstitute them as the objects they once had been, while respecting the alteration their matter had experienced.¹⁷ Due to the unique nature of the cache, we had no blueprint to follow, and our observations shaped our path. As the pipes grew, so did their musical interpretation hand in hand with reproduction experiments. Yet, the reconstruction of pipe parts from broken fragments also needed to keep options for retreatment and rearrangement open should future studies lead to new interpretations.

The conservation of this group of auloi differed from more common practices of musical instrument conservation, as the instruments did not exist as entities prior to treatment. The playability of the ancient pipes was never going to be an option due to their degraded physical state. The corroded bronze tubes would not turn, for example, and far too many parts were lost to fully complete the pipes. Thus, important issues surrounding conservation of playable instruments regarding wear of original substances, replacement of mechanical parts, or choices of materials that impact sound were not of concern.¹⁸ Over time, modern replicas would be created to explore the musical potential of the Meroë cache, and 3D technology is likely to play an important role in their future study.

Conservation was accompanied by scientific examination and identification of materials and degradation products (see ch. 6). Once a deeper understanding of the materials was developed, further questions regarding manufacture arose. At the same time, we aimed to preserve the materials, as much as possible, unaltered for future analysis.

4.5.1. Physical Joints and Reconstruction of Section and Pipes

After rehousing, the interior bone resonators, bulbs, and reed cone fragments could be handled safely and in a more controlled way than before. Against a cleaner background, the shapes became more readable, and many possible joints became immediately recognizable.

The bone parts, especially, exhibited specific shapes, textures, and sometimes incised surface decorations, all of which greatly helped to identify joints. The green stain observed in varying color on many parts was caused by contact with copper tubes in burial, and not original dye, as previous researchers had assumed. Some of the bulbs carried decorative silver sleeves, now mineralized and of brown, warty appearance.

The outer bronze sleeves and tubes were far more difficult to join. The thin walls of the heavily corroded bronze bits are often at least partially mineralized. In some sections, the corroded metal was severely distorted and warped, complicating the reconstruction of the original shapes. But, the thin-walled copper alloy tubes also show distinctive patterns, related to the burial micro-conditions. These features occasionally allowed identification of fragments that belong to a tube or section of a tube.

In other instances, the bronze and bone sections had suffered significant disintegration, which made the exact identification of joints difficult. The similarity in fracture patterns observed on bone and bronze tubes could be the results of them having being subjected to similar forces; while breakage patterns may also be related to ancient technologies. The wood is so fragile that for the time being any manipulation of

17. The literature on the conservation and scientific study of ancient instruments is limited and only recently developing. In an email correspondence with Olga Sutkowska on June 2, 2013, Graeme Lawson provided an unpublished document, “Assessment of the Musical Instrument prior to Conservation” (2004), which focused on an Anglo-Saxon lyre and outlined principal considerations for approaching archaeological instruments. See also chapter 6.

18. For an introduction to theoretical and practical issues concerning the conservation of musical instruments, see Barclay 2004; Both 2009; and Howard 2022). Also, refer to the ICOM International Committee of Museums and Collections of Instruments and Music: Conservation of Musical Instruments, <https://cimcim.mini.icom.museum/#>.

it was avoided. It has shrunk and collapsed in many sections and was no longer connected to the bronze tubes, except for a few notable examples, which still retain sound holes (see fig. 5.2), and section 101, which contained bone and wood on the interior of the bronze tube.

The adhesive used in the treatment was Rohm+Haas Paraloid B 72 (a conservation grade ethyl-methacrylate copolymer). It was prepared in a variety of concentrations of roughly 5-25% wt/vol in acetone and applied with a small brush to the break edges of elements that needed to be connected. Excess adhesive was brushed off with acetone. The resin remains reversible, does not darken, and does not preclude future treatment nor reversal of joints. In fact, reversal of joints was required frequently during the project, as sections grew, gaps needed to be filled with newly identified parts, or new connections needed to be made with difficult access due to the shape of the break edges. In a limited number of joints,



Figure 4.42. Susanne Gänsicke in the Objects Conservation laboratory of the MFA with trays of sorted auloi sections and segments during treatment (April 17, 2013). Photograph © Museum of Fine Arts, Boston.



Figure 4.43. Attaching parts of broken bone to form an almost complete bulb. Photograph © Museum of Fine Arts, Boston.

Japanese tissue paper was used on the interior to support thin break edges and lend further stability to the mends.

A significant number of bronze and bone slivers were not recognizable as a tube section and held no meaningful information at first. However, over time, it was possible to join a surprisingly large number of broken bits and to reconstruct longer bronze tubes, entire bone sockets, bulbs, and reed cones (figs. 4.42 and 4.43). Some new sections now consist of larger numbers of small, joined slivers.

Many pipes are formed by numerous short bronze tubes, joined with sockets and tenons of the inner bone lining. Identification of joints between the tubes was only possible when the interior bone lining protruded at the edge of a bronze tube section and connected to their counterparts on other sections. Some significant sections could be connected using these inner resonators (see fig. 3.4). For the majority of sections, however, this was not the case as the original interior wood and bone resonators had been either lost or were now present as separate fragments. In cases where the bone lining was separated from the metal tubes, joining tube sections based on the material evidence alone became almost impossible.

Despite the extensive reconstruction that was achieved over the course of eighteen months, there was a limit to what I could accomplish in reconstructing the pipes without intimate knowledge of ancient auloi and their working mechanisms (figs. 4.44–46). In May of 2015, Stefan Hagel (Austrian Academy of Sciences), Peter Holmes (Middlesex University London), and Olga Sutkowska (then Universität der Künste Berlin), joined the project for a first two-week study session at the MFA (see ch. 3). Their scholarship in music archaeology and detailed studies of auloi was indispensable to make further sense of the Meroë auloi cache. At that point, neither the implications of the project and its timeframe nor the outcome, could be estimated.

The music archaeologists began sorting tube sections by internal and external diameters and other distinctive features, and tentative arrangements of the first double pipes were made. For several sections, the two photographs of the fragments in situ (figures 4.5 and 4.6) were helpful, and corrosion patterns on the outer bronze tubes were considered throughout to aid in possible joints.

As the theoretical work continued, the scholars would ask me for elements with specific features. After years of working together we knew many of the fragments well and work took on an aspect of communal puzzling. For example, Stefan would task me to find him a hole, and more than once, even the thinnest sliver with only a half-moon section of a hole was valuable, or often finding a small piece with a distinct edge proved critical in forming connections and reconstructing longer tubes. Concentrated search for links became easier as the pipes grew in size, and the number of loose fragments decreased. Items became familiar, and their shapes were retained in our memory. We even developed nick names for some fragments, such as “the wolf,” a small tube section that resembled a popular image of a wolf howling to the moon.

Over time, new goals developed, new approaches to the organization of the material and its interpretation. The development of an inventory database served an important purpose allowing tracking and identification of sections (see chs. 3 and 5). Two hundred thirty-two individual items were numbered and were entered into the inventory (see ch. 5), including bronze tubes and tube sections, knobs, rings, sliders, chimneys, bone bulbs and reed holders.

Altogether, from 2015 to 2024 we convened in various configurations of the team for nine study sessions in Boston. A first research report was presented at the 19th International Congress on Ancient Bronzes at the J. Paul Getty Museum in 2015.¹⁹ From August 2019 to May 2022, the work on the objects by our team in Boston ceased due to the pandemic.

With the completion of the project in May 2024, we had assembled twelve pipes consisting of six pairs of pipes or auloi (fig. 4.47), which formed three distinct groups. As discussed in chapters 3 and 7, the arrangement of these items is based on physical evidence, ancient literary sources and musical traditions, as much as on musical evaluations. The six instruments were named as follows: the long pipes (LP), the short pipes (SP), and the wooden pipes (WP).²⁰

19. Gänsicke and Hagel 2017.

20. LP (24.3578, 24.3579, 24.3580, 24.3581), SP (24.3582, 24.3583, 24.3584, 24.3585), WP (24.3586, 24.3587, 24.3588, 24.3589).



Figure 4.44. Tray 8, mostly bone fragments, and tray 1, mostly bronze fragments, before treatment and during treatment after many sections had been joined (April 16, 2015). Photograph © Museum of Fine Arts, Boston.

4.5.2. Considerations for Long-Term Preservation

The pipes are now housed in two custom built, state-of-the-art storage trays, created by Brenda Breed, Senior Collections Care Specialist at the MFA. The long pipes are kept in one large tray, the wooden and short pipes co-inhabit a second box (see figs. 4.48 and 4.49). See chapter 7 for the layout of the separate sections in the individual pipe compositions, which allow tracking of the exact location of the individually numbered sections, and will serve as future reference or blueprint for their correct arrangement.

Still, today, hundreds of loose smaller bronze elements, mostly broken away from the external layers of existing sections, remain, as do many bone sockets, and smaller bone fragments. These have now been sorted into six boxes, very much as in a puzzle game, into groups with specific features: (1) bone with a small amount of silver; (2) wood; (3) bronze: rings; (4) bronze: fragments of tube walls and slider guides; (5) bronze: fragments of tube walls and slider guides; (6) bronze: reed holders and other miscellaneous parts (figs. 4.50–4.52). For bronze, those also include subgroups of thin wall sections, sections with edges, sound hole sections, slot sections, and rings. The bone fragments consist of pieces with worked edges, sound holes, sockets, larger flares, and small reed cones. The wood has neither been treated nor sorted and is contained in one dedicated storage tray.²¹

Over the course of the project, many physical joints that were beyond doubt were solidified with adhesive as described above. Many bronze tube sections now consist of numerous smaller slivers of bronze and similarly, bone items such as reed cones and bulbs were formed from many smaller pieces. We decided,

21. The boxes are registered in the MFA collections: 24.1821.1: Bone sockets and reed holders, silver sleeves; 24.1821.2: Wood fragments; 24.1821.3: Bronze rings; 24.1821.4: Bronze fragments, tube walls, slide guides; 24.1821.5: Bronze reed holders, flares, etc.; 24.1821.6: Loose fragments of tube walls.



Figure 4.45. Tubes and other sections from trays 1 and 2 prior to evaluation by music archaeologists (April 16, 2015). New storage trays allowed the arrangement of tubes adjacent to each other for better visualization. Photograph © Museum of Fine Arts, Boston.



Figure 4.46. Tubes from tray 3 prior to evaluation by archaeologists (April 16, 2015). Photograph © Museum of Fine Arts, Boston.

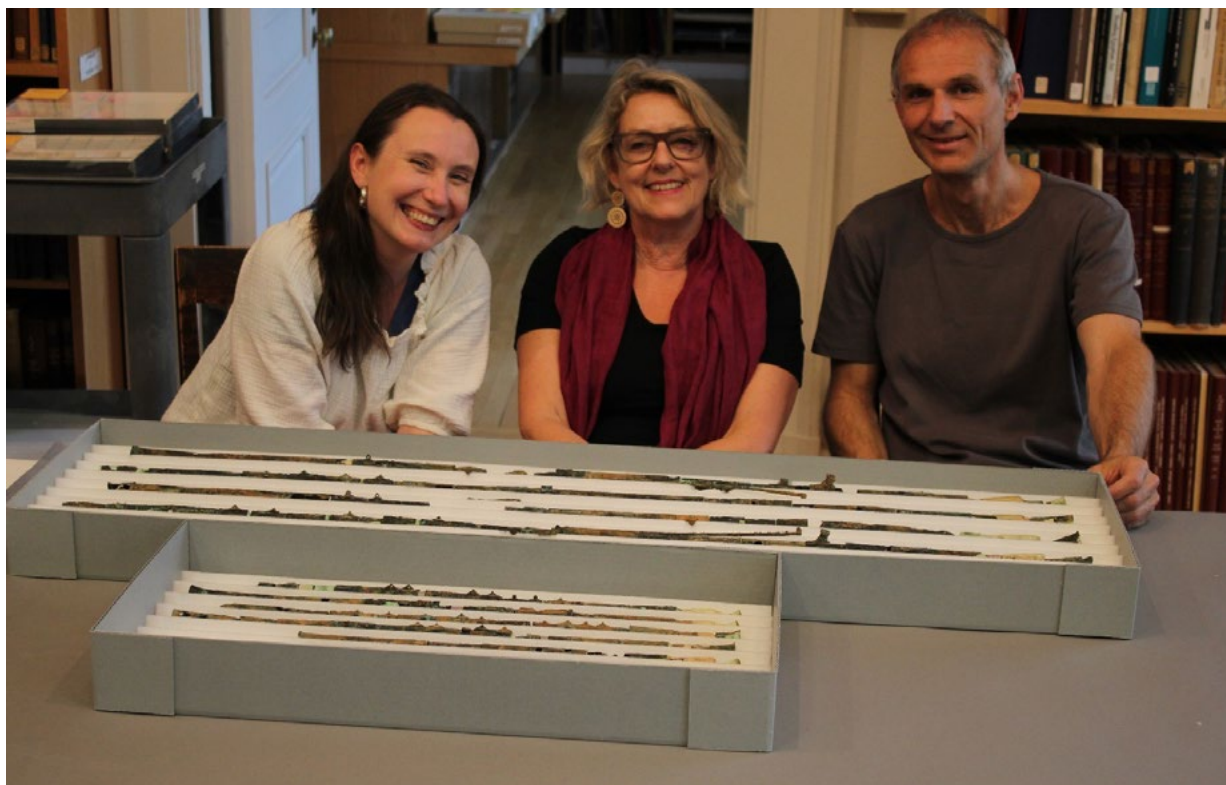


Figure 4.47. May 24, 2024, was the last working day of our team with the auloi cache in Boston. From left to right: Olga Sutkowska, Susanne Gänsicke, and Stefan Hagel in the library of the Department of Ancient Egyptian, Nubian and Near Eastern Art, Museum of Fine Arts, Boston.

however, not to join all the individual tube sections, even if their adjacencies have been formalized in the grid patterns, musicological interpretation and now this publication, to allow access for future research and analysis, or even new arrangements.

In the same vein, no cleaning was carried out at all, no adhering soil was removed, and importantly no removal of corrosion was attempted (neither by mechanical nor chemical means). Also, no treatment for “bronze disease” was attempted. While isolated patches of light green corrosion suggested the presence of chloride corrosion products, confirmed by analysis as atacamite and paratacamite (see ch. 6), over more than twelve years of study and handling we did not witness active degradation or further powdering. Storage will be provided by sealed metal storage cabinets, fitted with silica gel, which contain other ancient metal objects of the ancient Egyptian and Nubian collection, where the Meroë auloi can be monitored over time. We deemed the application of the standard corrosion inhibitor Benzotriazole, with immersion into solvent baths, rinsing, and subsequent coating with an acrylic resin as too invasive given the virgin nature of this find.

The decision to keep the treatment minimally invasive is based on several reasons. Although the current interpretation and arrangement of the pipes are firm, future research may offer alternative interpretations that require further examination and possible rearrangement of the tubes. As mentioned at the beginning of the conservation section, this unique cache has never been treated and remains free of contaminants and modern materials, except for the small amounts of adhesive and tissue paper used during our project. The auloi materials still harbor much information; for instance, bone analysis has only provided limited insights about species so far. There may be other compounds we have not yet identified, such as organic substances like glue or other surface treatments that we have not yet recognized. Future analytical techniques will likely provide additional opportunities for material identification and interpretation. Much more remains to be explored about the material choices and ancient technologies that led to the auloi’s production, as well as to their deterioration. For the time being, we hope our work will now allow deeper engagement with and appreciation of this find, which we had the privilege of dissecting and reconstructing.



Figure 4.48. The four long pipes in their new storage boxes. From top to bottom 24.3578, 24.3579, 24.3580, 24.3581.



Figure 4.49. The eight short pipes in their new storage boxes. From top to bottom: 24.3582, 24.3583, 24.3584, 24.3585, 24.3586, 24.3587, 24.3588, 24.3589.



Figure 4.50. Storage boxes with remaining broken bronze fragments (24.1821.6, 24.1821.4). SC492111. Photograph © Museum of Fine Arts, Boston.



Figure 4.51. Storage boxes with remaining broken wood, bronze and bronze fragments (24.1821.5, 24.1821.2). SC492110. Photograph © Museum of Fine Arts, Boston.



Figure 4.52. Storage boxes with remaining broken bronze and bone fragments (24.1821.3, 24.1821.1). SC492112. Photograph © Museum of Fine Arts, Boston.

5 Description of the Corpus

Susanne Gänsicke and Stefan Hagel

The complexity of the auloi from Meroë is such that hardly any of the sections from which they were put together is made just of a single material. Almost the entire instruments were clad in thin layers of shiny metal, except the white bulbs of bone—but even of these, many were adorned with an incredibly fine band of silver. In the following, we will describe the various types of components in terms of their materials, shapes, and functions, at times adding a few considerations about how they may have been produced. We start with a brief list of the used materials and their respective purposes. Item numbers refer to the catalogue of parts at the end of this chapter

5.1. Materials

5.1.1. Wood

Wood survives mostly in small fragments dissociated from the pipes (fig. 5.1). The most notable exception is a length of tubing with toneholes (fig. 5.2), which, in spite of being shrunk and warped, preserves about the original distance between the holes, as a comparison with its original bronze encasing shows. Wood seems to have been used exclusively for tube cores and was thus never exposed to the view. It replaced the scarcer resource of suitable bone wherever no rotary-sleeve mechanism was mounted. Apparently, not even the famously hard olive wood that we find employed (see chapter 6.7) was deemed reliable enough to support such a mechanism, which might jam at the slightest deformation of the cylinders, brought about by absorption of humidity from the player's breath.¹ Wood would have been comparatively easy to drill and turn on the lathe and could be made in longer sections than was possible for bone tubing.

Pipes without any rotary sleeves are thus expected to have contained wood throughout the main tube. On the others, wood would find its natural place, on the one hand, between the bulb and the highest fingerhole, and on the other, at the lower end of the instrument, from the bell up to the first sleeve mechanism. Consequently, flaring ends without a preserved core are typically bells, while short ones with bone cores rather form reed cones. The use of wood at the upper end is difficult to prove for the Meroë cache, because the tubes in question are now empty. However, a tiny hole in one small wooden fragment (226) almost certainly represents a *sýrinx* and would thus have been located close to the mouth end, just below the bulb (fig. 5.1, small box left of top center).

5.1.2. Bone

Internal bone tubing is produced from the straight parts of certain ruminant metatarsals with suitable diameter and cavity and was therefore assembled from relatively short sections. The individual tubes were joined by spigots and sockets. Different kinds of bones must have been used for the bulbs and the reed cones where these are of significantly larger diameter. Only in the case of the bulbs, the bone would have remained visible.

Often fine grooves are incised on the surfaces of spigots, tubes, and flares. Whatever glue or sealant was used between bone parts as well as between bone and metal, these grooves must have helped securing a firm connection.

1. A wooden core with mechanism might however have worked for thicker pipes with substantially solid walls, as examples from Pompeii, now in the National Archaeological Museum of Naples, indicate (inv. 119890A).



Figure 5.1: The preserved fragments of wood. Photograph © Museum of Fine Arts, Boston (SC492110).



Figure 5.2: The core of 015, representing the best-preserved wooden element.



Figure 5.3: Reed cone 160 before conservation. From the left side, a counterbore receives the spigot of the bulb, which is here still stuck inside, but not pushed up to the limit. The bone wall of the socket measures merely 0.5 mm.

The bone parts are produced with incredible precision. Inside the lower part of a reed cone (the part that went over the spigot that extends from the bulb), the bone wall was typically much thinner than a millimeter (fig. 5.3); it was probably reduced to this point only after fitting it in its metal cylinder.

5.1.3. Metal

5.1.3.1. Bronze

Bronze was primarily used for the encasing of the tubes, but also for both kinds of mechanical devices, rotary sleeves and sliders. The encasing was always formed in sections, normally a few centimeters long, but in extreme cases—always without any fingerholes—measuring more than 27 cm. The tubes are perfect cylinders, with walls less than half a millimeter thick, produced without any seam. In places where single-layered bronze alternates with the two layers required by the rotary-sleeve mechanism, the ensuing difference is normally balanced not by substantially thicker single layers, but by a wider core of bone or wood. In this way, weight is kept to a minimum, which is of the highest importance in the case of the longest instruments (see chapter 7.2.3). In order to maximize the stability of the pipes, the places where inner and outer bronze sections meet respectively are often offset. On the other hand, we also encounter instances of quasi self-contained sections, which could be assembled separately and where the boundaries are therefore aligned; consequently, the integrity of the instruments rests here fully on the bone core.

For the flaring lower ends of the pipes, the tubing must have been hammered into shape, in a process probably assisted by repeated annealing. The working and thinning of the material made these regions especially vulnerable. We may envisage the use of mandrels in order to achieve precise standardized shapes. At the very end, the metal was finally bent over the edge of about 90°, to be shaped into a tiny recession, displaying the highest level of craftsmanship. At the instruments' upper ends, however, the flaring bronze parts of the reed cones are made in separate pieces, which may be evidence that the bronze was here actually spun over the core (or a mandrel of the same shape). The termination over the edge was however manufactured in the same way as on the lower ends (fig. 5.3).²

Where two layers of bronze formed rotary sleeves for closing and opening toneholes at the player's discretion, these had to be airtight but still movable with sufficient ease.³ Being highly wear-resistant,⁴ tin bronze (see chapter 6.3) is an excellent material for that purpose, as it guarantees long product life.

In most instances, these two layers are now firmly corroded together; in others, part of or, rarely, the entire outer layer has detached. In such cases, it is sometimes no longer possible to determine the position of the knobs that served as levers for turning the outer cylinders around the inner (see chapter 1.2). The various shapes of these knobs are described below; they also seem to have invariably been made of bronze, while it is unclear whether these small parts were also cast wholesale or involved combining elements that had been preproduced in different ways.

The long thin sliders, finally, may represent the most stunning examples of ancient metal casting in the find; see the description below for details. They were held in place by narrow bronze strips serving as guides, which may have been cut from sheet metal and bent to shape.

The most robust bronze parts, finally, are what we have come to call “chimneys”: short, slanted tubes fixed to the side of the main tube over a tonehole. Intricately ornamented, these were almost certainly also cast in lost-wax technique.

5.1.3.2. Silver

Silver is found only as a decorative element, and only on bulbs—but not on all of them. Of the four larger bulbs, only one pair (135, 137) show applied silver, while the other seem to have exhibited plain bone surfaces (136, 138). Of the eight smaller bulbs, all but a single pair (064, 157) appear to have featured silver bands (111, 134; 139, 140; and 156, whose companion is almost entirely lost).

2. This conforms with the impression of Peter Holmes when inspecting those items.

3. Closely fitting lathe-turned cylinders, albeit of much larger diameters, were also used in ancient water pumps. For turned air-pump components used in a musical instrument, the water organ, compare Vitruvius, *On architecture* 10.8.1.

4. E.g., Lunn 1965. Note, however, that the process of annealing would diminish bearing properties, which can be restored by cold-working.



Figure 5.4: Bulb 111 with remnants of silver and silver-induced discoloration on its lower part.

Surprisingly, these silver sleeves are found on the necks of the bulb sections, where the external diameter tapers down between the main tube and the bulb itself, so that the bulge of the latter stands more clearly apart (fig. 5.4). Since the items are not assembled in the region of the neck, but made of a single piece of bone, it is difficult to see how a narrow metal band, which could not be slipped over either end, might have been attached there. Do seams escape us? Or was the silver actually spun onto the bone, which would seem an extraordinary feat?

5.1.3.3. Solder

Fastening the various types of attachments—knobs, chimneys and slider guides—on the tubes required a suitable solder, alloyed from tin and lead. In order not to damage the organic core material, soldering was almost certainly done before assembling the layers of tubing.

5.1.3.4. Tinning

Tin may also have been used to change the look and probably the mechanical properties of certain bronze parts. This particularly concerns the sliders, which touched the tubing over a length of more than 30 cm, which were without doubt operated during performance, and for which low friction was therefore paramount. Tin, in the form of a thin surface film, is a well-known means of reducing friction on mechanical parts, especially at temperatures above 13 °C,⁵ as are typical not only for the Nile Valley but generally for wind instruments, which warm up through the player's breath. These tinned accessories occasionally appear to have left whitish traces on the tube, which may be related to tin corrosion products and helped determining the original configurations. In other places, prior exposure to a tinned surface appears to have triggered a particular kind of dark corrosion that may sharply stand out from its surroundings (see chapter 7.2.1 with figures 7.44, 7.46, 7.47, and 7.48).

5.2. Parts

5.2.1. Tubing

Although, due to various types of corrosion, precise original diameters are often difficult or impossible to measure with precision, the surviving cylindrical parts clearly fall into two categories: belonging either to narrower tubes of about 14–15 mm diameter or to wider ones measuring about 16 mm. Both types are found to contain bone lining as well as wood fragments on the interior. Where we have empty metal tubes, we must assume that the core was lost, which is more likely in the case of wood, due to its degradation and shrinkage. But bone could also be displaced—we find several instances where the holes in the encasing no longer align with those in the core (fig. 5.5). In one instance, the short fingerhole section 101, a direct connection between bone and wood as core materials was preserved—bone tubing from a region with rotary sleeves socketing into wood that would reach down to the bell.

For both diameter classes, we find examples of simple tubes without any holes, tubes with simple fingerholes, tubes with rotary sleeves, and also sections ending in flaring “bells.” Sliders and rectangular

5. See Buckley 1975: fig. 8.



Figure 5.5: Item 067, with displaced bone core.

toneholes, on the other hand, are only found associated with the wider type. Round holes are typically not circular but slightly elliptic, the longer diameter being aligned with the tube: these cannot have been simply drilled but must have been carefully filed.

5.2.1.1. Spacers

Sections of tubing without toneholes are conveniently called “spacers.” These would typically be required between bulb and highest fingerhole, but often also in the bass regions or between fingerholes and bass toneholes. The relevant items include: 008 012 013 014 016 017 018? 019 024 027 033? 035? 046 066 074? 083 084 087 102 123? 130? 133 209? 211?.

5.2.1.2. Spacer rings

Very short spacers take the shape of rings. These typically occur between sections with rotary sleeves, in case there is sufficient space between adjacent toneholes. As such spacers could be glued to the core, they offer the considerable advantage of preventing inadvertent rotation of an adjacent sleeve when its neighbor is operated. Often only a couple of millimeters wide, loose spacer rings are very fragile and some may have been lost. Apart from those still attached to larger pieces, they comprise the following items: 126 141 142 145 150 151 201 202 203 204 205 206 231 232.

5.2.1.3. Slider tubes

The unusually long tube sections on which the sliders were mounted by means of three “slider guides” can be viewed as a special example of spacers. Notably, these slider tubes do not themselves contain the toneholes that were operated by the sliders. Instead, the sliders’ lower end extended a few centimeters beyond the end of these tubes. Indeed, it would not have been possible to create the tonehole precisely at the required position once the slider was mounted, and it may have been inconvenient to mount the slider precisely enough over a prefabricated hole. Separating the sections containing slider and hole thus guaranteed the flexibility required for exact adjustment. Similarly, the upper part of the sliders extended beyond their tubes, obviously into a region where fingerholes were manufactured in individual sections.

The four slider tubes are assigned the following numbers: 032 036 050 085. Only on 050 was the slider still attached to the tube by means of two guides; even here, though, the third had been ripped off when the upper part of the slider was bent away from the tube. Tube 085 stands out for a unique connection to its neighbor, via a short bronze cylinder that is inserted into its end and must similarly have been received by the external metal layer of the adjacent tube (see chapter 7.2.1).

The sliders themselves are masterpieces of bronze casting, technically and aesthetically (fig. 5.6). The round plates that went over the tonehole are shaped as little sea shells, only about 7 mm in diameter. Tiny dolphins⁶ hold those shells in their snouts; from their tails the straight rods extend, with mostly rectangular cross section, throughout their longest part finely adorned with parallel grooves that display remains of tinning. About 5 cm above the shell, the rods bend at a right angle half around the tube, then again at a right angle upwards. From the dolphin up to that “bracket,” the upper side of the rod may feature a finely

6. Ridges running from the edges of the snout to the back, now visible mainly on 050, appear to indicate the extent, albeit exaggerated, of the toothed whale’s melon, which is often distinct in such a way in the ubiquitous bottlenose dolphin (*Tursiops truncatus*).

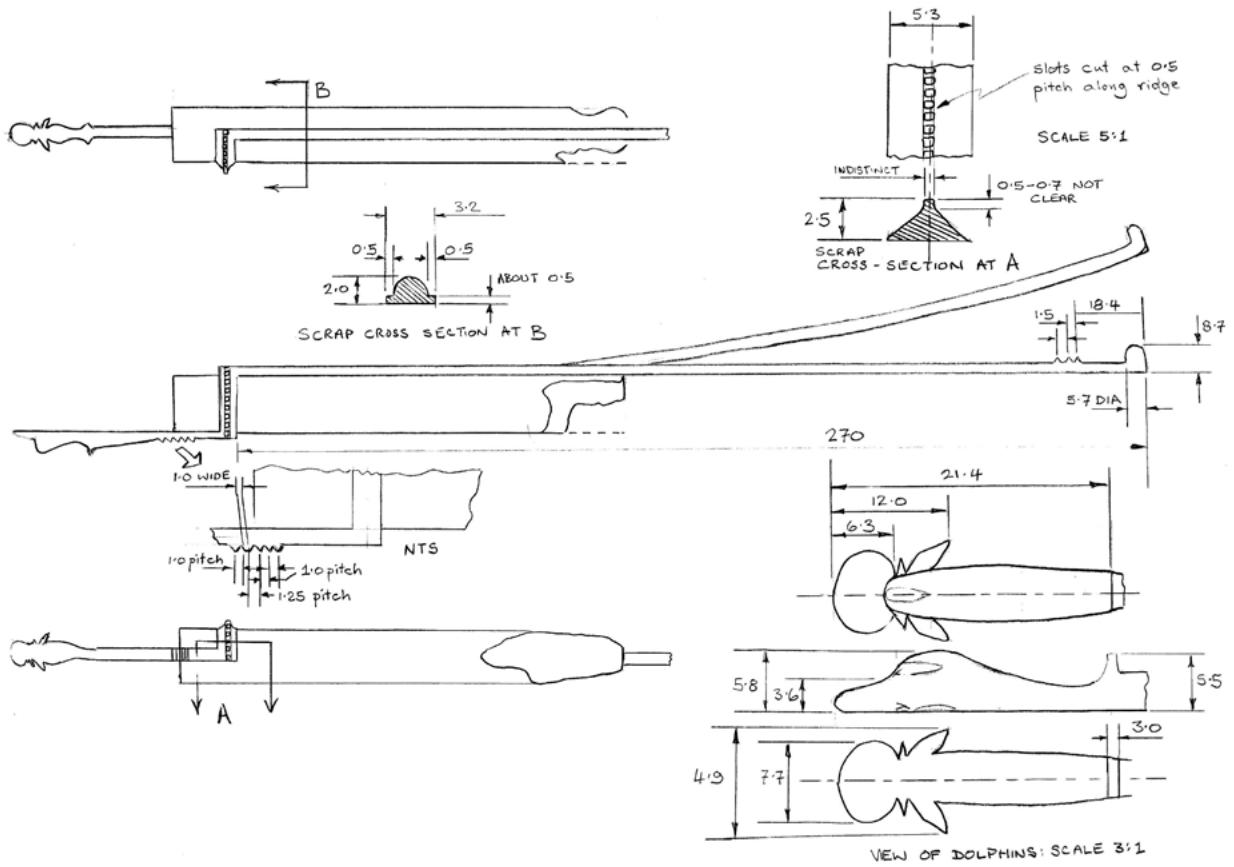


Figure 5.6: The sliders. (a) Complete slider 050 from above. (b) Drawing of 050 by Peter Holmes. (c) Dolphin and lower part of rod 053. (d) Upper rod 051 with tinned knob.



Figure 5.7: Slider compound 050 with two slider guides reattached at their original positions. Toward the right, solder traces of the third guide can be discerned.

toothed ridge, while the part that curves around the tube is broader, with a curved cross section topped by a continuous ridge. The upper ends feature globular knobs on slightly wider rectangular plates, preceded by a series of sharp ridges running around three sides of the rod. For all we see, the entire sliders may have been cast in a single piece—an extraordinary feat given their small diameter. Unfortunately, only two survive in their entire length. The relevant items are: 050, which includes the tube; 051, which must represent the upper end of either 052 or 053 and has lost 2.5 cm since the excavation; 052, whose upper end is missing; 053, consisting only of the dolphin end; 054–032–117, where the bracket is corroded to the tube, while both ends broke off; and possibly 230, seemingly a knob, that we only know from an excavation photograph.

The sliders were attached by “guides,” apparently cut from thin bronze sheet and bent to match the rod precisely (fig. 5.7). Two of them were soldered on the tube above and below each bracket in such a way that they restricted the path that the sliders could travel exactly to the diameter of the shells, so that the holes could be just fully opened and fully closed, but preventing any unnecessary movement. A third guide was located further up the tube, ensuring the precise orientation of the rods as well as preventing the exertion of angular forces, whose leverage might otherwise easily have ripped off the lower guides. The guides are associated with the following item numbers: 050 212 213 214 215 216 217 218 219 220.

5.2.1.4. *Tubes with simple toneholes*

In the Meroë find, sections with toneholes drilled through core and only a single layer of bronze form a substantial minority. Nonetheless seven of them have thumbholes, so that apparently no less than four instruments had no rotary sleeves in their top regions. These would have included the thicker just as well as the thinner instruments, since we once more find examples for both classes. In the following list, the presence of unequivocal thumbholes—which of course are identifiable only on sections with at least two holes—is indicated by a “T”: 007 015 021T 028T 029 031 034T 039T 042 044 045 059T 060 063T 073T 081 089 091 100 101 105 109 113 131 200 227.

While most of the toneholes are round, we also find three that are formed into an elegant teardrop shape: 034, 039, and 059 (see also fig. 7.22 in chapter 7.1.3.1). Again, these are not confined to one diameter class.

5.2.1.5. *Tubes with toneholes and rotary sleeves*

The majority of toneholes comes with the rotary-sleeve mechanism, operated by a knob. Most of the respective holes are placed in a section of their own, maximizing flexibility in setting up different scales. The length of these sections ranges between a mere 17 mm and more than 4 cm. In two instances, however, both belonging to the slenderer class of tubing, three hole positions are combined in single sections. One of these, item 048, opened and closed all three together, while another, 043, was designed for three different states in a complex manner, which will be explained in chapter 7.1.2. The ends of each sleeve may carry one or two slightly raised ridges (fig. 5.8). Presumably these are intended as reinforcements at the points where rotation caused friction with the adjacent sleeve or spacer, while the central part is kept as thin as possible in order to minimize the weight of the instrument.

While round toneholes are found with and without sleeves, all rectangular openings are furnished with sleeves. This is almost to be expected, since the large rectangular toneholes cannot be covered by a finger: as a consequence, any such hole without a sleeve would have to be the lowest on its pipe. Whatever shape the holes took, they were almost certainly manufactured independently on both layers: when drilling or filing two tightly fitting cylinders at once, there is great hazard that some overlap created in the process will jam them irretrievably.

In the following list of relevant items, rectangular holes are marked with “R,” and thumbholes, with “T”: 001 002 003 004 005 006 009 010 011 020 022R 023 026R 030 040 041R 043TT 047 048T 057 061 062 067 068 069 070T 071 072 075



Figure 5.8: The rotary sleeve on item 057 with two ridges at the left and one at the right end. The knob 189 it once held is still detached.



Figure 5.9: Triangular knob 193, from the side (above) and from below (right).

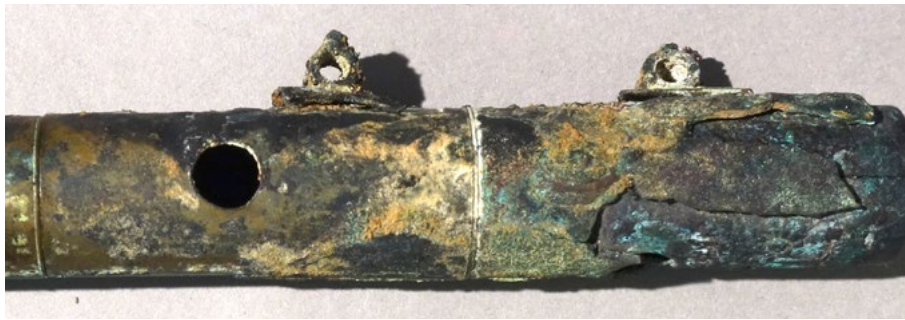


Figure 5.10: Ring-shaped knobs 143 and 173, reattached to section 047.



Figure 5.11: Globular knob 197, reattached to section 104, from the side and from above.

076 077 078 079 080 082R 086 088 094R 095R 096R 097R 098R 099R 103 104 114 115 119 121
144 152 155? 207 208 210?

The knobs that facilitated turning the external cylinders around the internal metal tubing rest on slightly arched plates that match the curvature of the tube and are cut out at the sides to different degrees. They come in three distinct kinds: with triangular, ring-shaped, and globular projections. The overwhelming majority are triangular, when observed from the side of the instrument, with a hole drilled through them and a small “crown” bearing a groove at a right angle to the tube (fig. 5.9). A few are in the form of a small ring, much like those known from Pompeii (see chapter 1.2 with fig. 1.7), also with grooved crown (fig. 5.10). Both these types may have been furnished with windings of soft thread, cushioning the otherwise uncomfortable edges of the bronze (see chapter 6.8). The last kind are simple globular knobs (fig. 5.11). In the following list of relevant items, globular knobs are marked “G,” and ring-shaped knobs, “R”: 001 002 020 071 072R 075 114 124 127G 128 129 143G 171R 172 173R 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197G 198 207 208.

Although most knobs had become detached from their sleeves, some only long after the excavation, the original place of each of them could be determined by the highly characteristic plate shapes that had normally left unmistakable imprints on the corroded tubes. However, ten knobs are lacking. As these



Figure 5.12: Section 001 with “cut” near the right rim.

relatively solid bronze parts are unlikely to disintegrate, one would wonder how the excavators could have overlooked them, in view of all the tiny fragments they did retrieve. But perhaps this was not the case. Interestingly, the places to which these missing knobs had once been soldered are far more corroded than those of the extant ones, sometimes hardly revealing the merest shadow of a trace. It therefore seems that these surfaces had been exposed for much longer. Apparently, the absent knobs had already been ripped off when the instruments were buried, probably in the course of their destruction (see chapter 7.4.4), and may never have reached the deposit. The others would have slowly come off in the ground, while still protecting the underlying surfaces, or become detached during or after excavation.

Generally, the knobs sit laterally on the tube when the respective hole is open, a little more than 90° displaced from its center. Some are even opposite the hole, but this seems to concern toneholes that were never covered by the fingers. Fingered holes—with the natural exception of thumbholes and one secondary side hole to be discussed below (chapter 7.1.3.1)—never deviate very far from a straight line, their precise placement apparently being suggested by ergonomic convenience. Below the range of the hands, however, toneholes may appear anywhere around the tube; as a corollary, knobs can no longer be aligned either.

One of the great technical surprises of the find was the presence of short incisions close to the rim of almost all rotary sleeves (fig. 5.12).⁷ Apparently, these hair-thin slots were always cut at the same height as the knob, with the finest of tools; they are found either on the upper or the lower end of their sleeves. Many are badly preserved because the thin bridges between their ends and the outer rim break easily; often only the offset between two smooth rims indicates the former presence of such a “cut.” We have been able to identify between 50 and 53 of them on the following items, using also the x-ray images (“+” signs indicate the presence of one more incision on the same piece, when one item contains multiple sleeves): 001 002? 003 004 006+ 009 010+ 022 023 026? 030 040+ 041 047+ 057 062 067 068++ 069 071 072 075+ 076 077 078+ 079+ 080 082 086 088+ 094 095 096 097 098? 099 103+ 114 115 119 121 144.

Among the pieces of larger diameter, only two clearly miss such a cut. One is 061, which is the shortest section in this class. The other is 005, an otherwise perfectly inconspicuous part; we appear unable to account for its abnormality in this respect.

There are some more sleeves without incision among the narrower items. These involve the only sections with multiple holes, 043 and 048; one section of 067—again a particularly short one; both sections of 070; 011; 104; and probably 020. Many in this group also share other features, although no strict rule emerges. Items 020, 048, 070, and 104 have globular knobs, but not so 011, 043 or 067. Items 043, 048, and 070 include a thumbhole, as does 104 according to the reconstruction proposed below, but not so 011, 020, or 067. While there may be no rule that would allow us to predict each “missing” cut,

7. These cuts are mentioned in Sutkowska 2015: 417.

we might nonetheless observe potentially general rules that preclude such cuts: none of the five sections with globular knobs has one, nor does any that includes a thumbhole.⁸ However, 011 and 067 stand out unexplained.

What was the purpose of those incisions, which are hitherto unparalleled in other aulos finds? It is tempting to look for an interpretation as a means of restricting the movement of the sleeves, so that the holes can be opened and closed with precision. That would require a slot within which some kind of pin runs; what we observe, however, is much too thin for serving as such a slot. The answer may rather be found in the necessity to regulate the friction of the sleeve: when it becomes too loose, it might rotate of its own account when the tube vibrates with the generated soundwaves.⁹ Possibly, the segments that the incisions separated from the rest of the tube acted as a spring, by which the friction could be regulated: the slightest deformation of this narrow strip, most probably by gently pushing it inwards, would tighten the sleeve's grip on the internal tubing. In order to adjust the tension of this spring, one would of course need to take the instrument apart—hardly too difficult a procedure, if such maintenance work was carried out by professionals.

5.2.1.6. Chimneys

Three slanting side tubes are another exclusive feature of the Meroë find (items 065, 090, and 149). Firmly sitting on a large rectangular base with decorative openwork windows—almost everything appears optimized for weight!—they rise at respective angles of about 76° (065), 80° (090) and 82° (149) as square turrets with ornamented friezes and a cylindrical hole (figs. 5.13 and 5.14). The items were almost certainly cast in single pieces and may retain traces of tinning. They are of similar make but different sizes, evidently not mass-produced but accommodated to their particular function on a particular instrument, as will be suggested below (see chapter 7.2).

5.2.2. Bells

Most, if not all, pipes seem to have ended in a flaring “bell.” The flare, however, was probably a purely external feature: a comparison with other finds suggests that the actual bore remained about cylindrical down to the exit. A direct observation of the internal diameter at the exit is, however, impossible on the Meroë instruments, whose terminal flares invariably contained a wooden core. As discussed above, the flares were apparently hammered from the end of the cast cylinder and subsequently folded over the edge of the wood. Relevant items include the following: 025 037 049 091 092 107 116 120 123? 125 132?.

5.2.3. Bulbs

The Meroë bulbs have an unusual shape, comparatively long and therefore not particularly bulging. Also, the silver bands that decorate the necks of eight of them are not paralleled in Pompeii or any of the other better-known finds. We might therefore have concluded that these apparently idiosyncratic bulbs reflect the fashion of a particular local workshop, which perhaps produced for the demand of the Nile Valley—were it not for a single unprovenanced item in the Museum of Musical Instruments in Rome, which mirrors their construction in every detail (fig. 5.15, compare also 5.16). Not only has it the same general shape and comparable relative dimensions of both the lower spigot that was inserted into the main tube and the upper spigot over which the reed cone went, it also exhibits a similar narrow ledge at its lower end, before tapering toward the neck, it features remains of what seems to have been silver, and these remains are found in a recession in the region of the neck, with two slightly deeper bands at the upper and close to the lower end, exactly as found on the respective Meroë bulbs. Though the item in Rome may hypothetically have arrived from Egypt in modern times, this is just a remote possibility. More probably, either the design was commonly produced in a far wider region, or at least one of the finds had traveled much further in antiquity than we might have anticipated. The last option is perhaps the most likely, given the degree of structural coincidence.

8. In the reconstruction proposal below, another thumbhole will be suggested; however, the respective section is so fragmented that neither its knob type nor the presence or absence of a cut can be ascertained.

9. This has been observed on a replica of the Berlin aulos (Berlin Egyptian Museum 12461/12462), which features a single sleeve.



Figure 5.13: The smallest chimney, 149, from the side and from above, and the respective solder traces on tube 100.

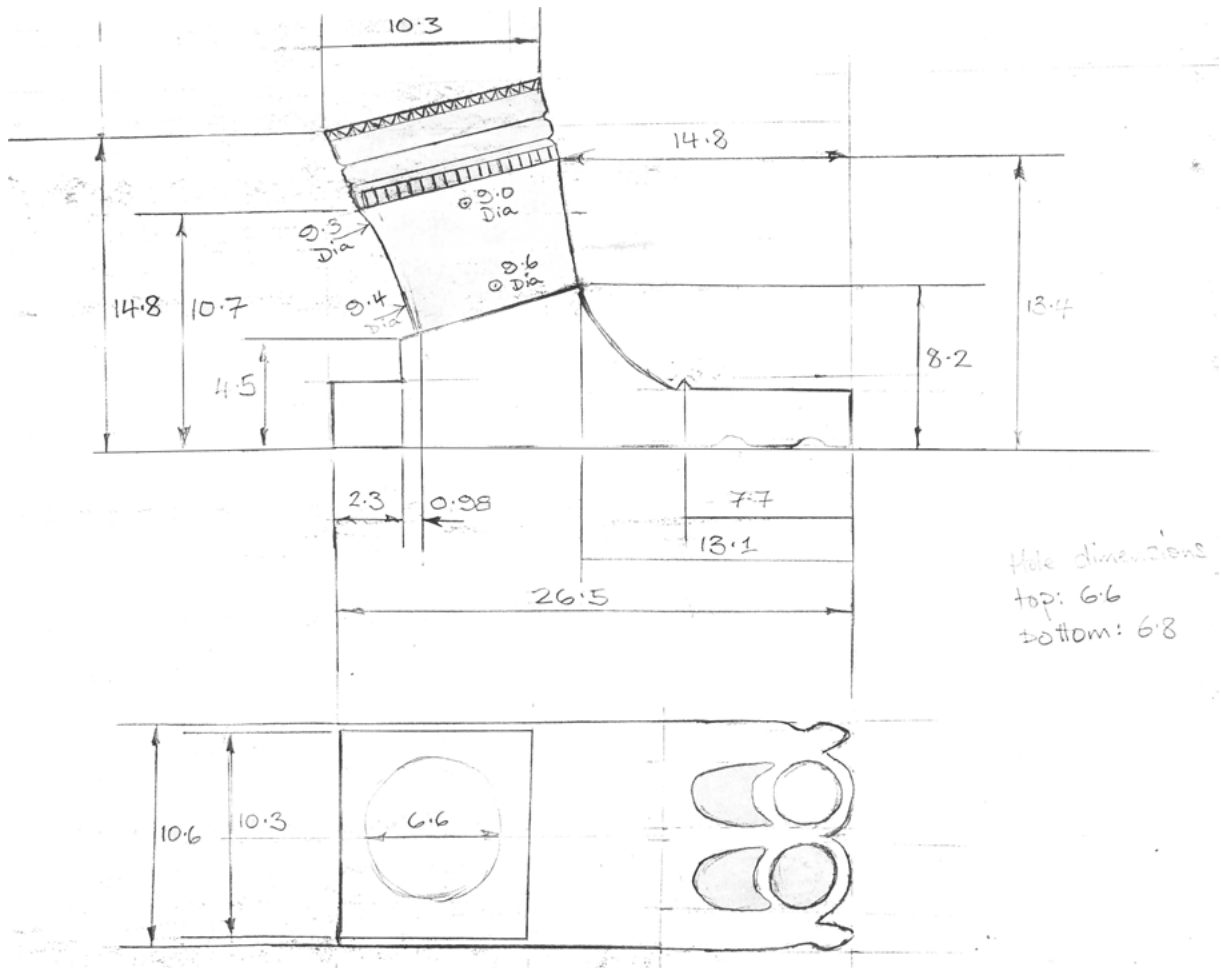


Figure 5.14: The intermediate chimney, 090. Drawing by Peter Holmes.

In spite of their general similarity, the Meroë bulbs come in several sizes, and indeed not all carry a silver sleeve. Unlike the item from Rome, some of them have a small *syrix* hole drilled either in their bulging parts or, in two instances, 135 and 139, in their lower spigots. In the latter cases, the hole had to be replicated in the metal tube and possibly a wooden socket; we have examples for both (metal spacer 016 fits with 139; for the wooden piece 226, compare above, with fig. 5.1). Of the four largest bulbs, whose diameter assigns them to the wider instruments, all feature a *syrix*, as does 139 among the smaller, and apparently also 148, of which only a fragment from the neck survives. But 111 and 134 have none. Where parts are missing from the crucial regions, we cannot tell: 064 might have had a *syrix* hole on the spigot (the reconstruction proposed below does not exclude that possibility either); 140, on the bulb; 156, on the neck; and 157, on either of the latter.

Finally, here is the complete list of relevant items: 064 111 134 135 136 137 138 139 140 148 156 157.



Figure 5.15: Comparing bulb 137 (above) with bulb Musical Instruments Museum Rome inv. 25511G (below). Lengths of bulbs without either spigot: 70 mm and 58 mm.

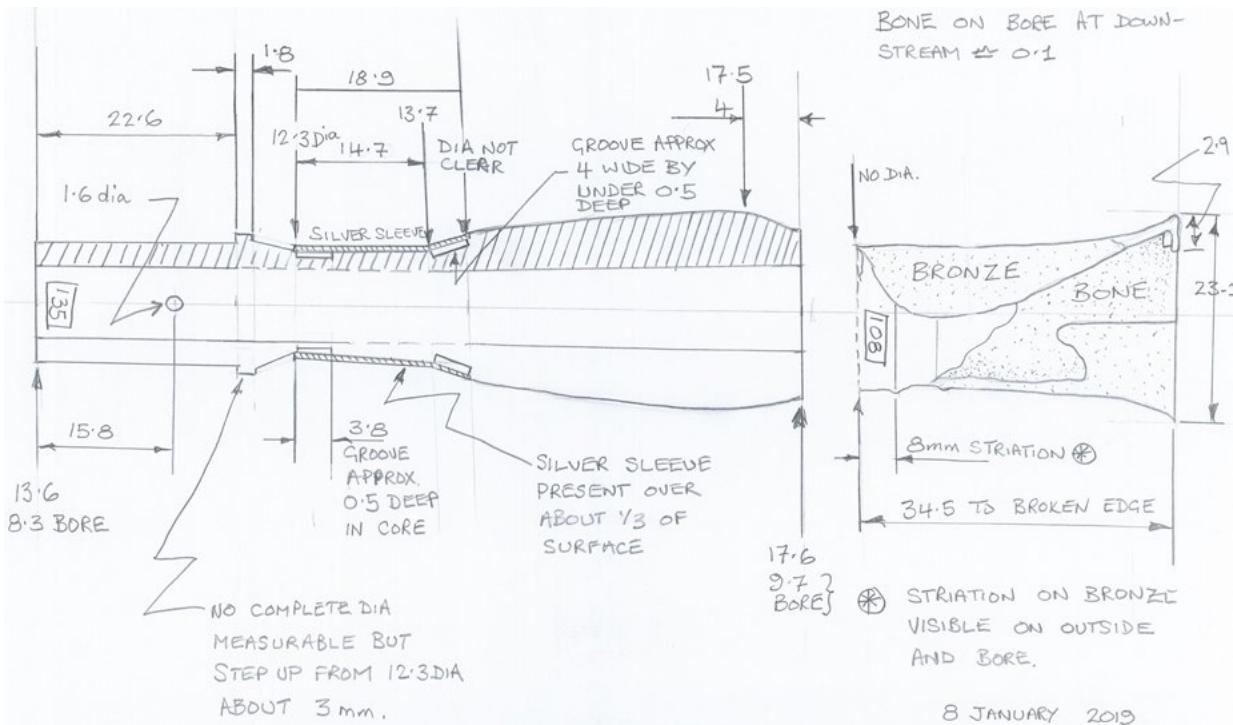


Figure 5.16: Drawing of bulb 135 (upper spigot missing) and reed cone 108 (lower end broken) by Peter Holmes.

5.2.4. Reed Cones

The last (and uppermost) functional parts are the reed cones. They consist of a cylindrical “foot,” which includes the socket that receives the upper spigot of the bulb, and an elegantly flaring section, which contains the socket for the reed mouthpiece (see fig. 5.16 as well fig. 5.3 above).¹⁰ Many of the

10. Because of their profile, reed cones have been mistaken for bells (Bodley 1946: 235; see Byrne 2002). The core material is generally a good guide, as is the presence of the reed socket, but also the separation of the metal encasing of flare and cylinder into two well-delimited parts that were at least sometimes made separately and may survive separately with smooth ends (e.g., 056, 058).

cones were heavily fragmented; but they could be joined to a state where it is possible to assert that their original number matched that of the extant bulbs. Nonetheless they remain in many more unconnected parts, for instance because the pairing of bone cores and metal flares is not always unequivocal, and even where it can be established, it may no longer be physically feasible. The complete list comprises: 038 055 056 058 093 106 108 110 112 118 122 146 147 158 159 169 161 199 223 224 225.

It is difficult to see whether all cones were of the detachable kind that could serve for fine-tuning the pipes to each other, or whether some of them were actually glued to their bulbs. At any rate, the cross-section that the broken item 160 had fortunately exhibited (again, fig. 5.3) strongly suggests that at least some were of the tunable sort: otherwise, the considerable gap between the ends of the bulb spigot and its socket would be difficult to explain.

5.2.5. Inventorized Unassigned Pieces

Finally, there are a number of fragments that appeared large and characteristic enough to warrant inclusion as individual items in the database rather than keeping them with the “rubble.” These comprise bone pieces, almost all of them sockets (162 163 164 165 166 167 168 169 170 221), a couple of bronze fragments (222 229), the mentioned piece of wood with a small hole (226), and even a lump of compacted soil that was extracted from a reed cone and preserves the step between bore and reed socket (228).

5.3 Catalogue of the Larger Fragments

Stefan Hagel and Olga Sutkowska

Shortcuts for measurements

Lng	overall length without spigot
Di	internal (bore) diameter
Do	external diameter
Sp1	spigot at the left end (typically the distal end)
Sp2	spigot at the right end (typically the proximal end)
Sp#L	spigot length
Sp#D	spigot external diameter
So1	socket at the left end (typically distal end)
So2	socket at the right end (typically the proximal end)
So#L	socket depth
So#D	socket internal diameter
H#	tonehole number #, counting from the left end
H#Pos	position of the centre of tonehole number #, measured from the left end, excluding spigot
H#Dl	longitudinal diameter of tonehole number #
H#Dt	transversal diameter of tonehole number #
H#Az	relative azimuth of tonehole, looking downstream, toward the bottom of the pipe (positive values indicate counterclockwise orientation)
H#S	shape of tonehole number # (R: rectangular; T: teardrop-shaped)
H#BPos	position of knob relative to the center of tonehole number #
H#BAz	azimuth of the knob relative to the center of tonehole number #
H#BS	shape of the knob operating tonehole number # (T: triangular; R: ring-shaped; K: globular)
Sct#	boundary of 'section' number #, measured from the left end, excluding spigot; may also be used for incised lines etc.
E1	left end of fragment
E2	right end of fragment
E#P=0	end of fragment is not preserved
E1T=B	lower end of fragment is shaped as a bell
E2T=R	upper end of fragment forms a cone for inserting the reed mouthpiece
Cuts	number of incisions in external sleeves

All measurements are given in mm, unless specified otherwise.

Approximate measurements are indicated by "≈" or "∼".

Where ranges are indicated by hyphens, they typically apply from left to right, e.g., Do=18-17.

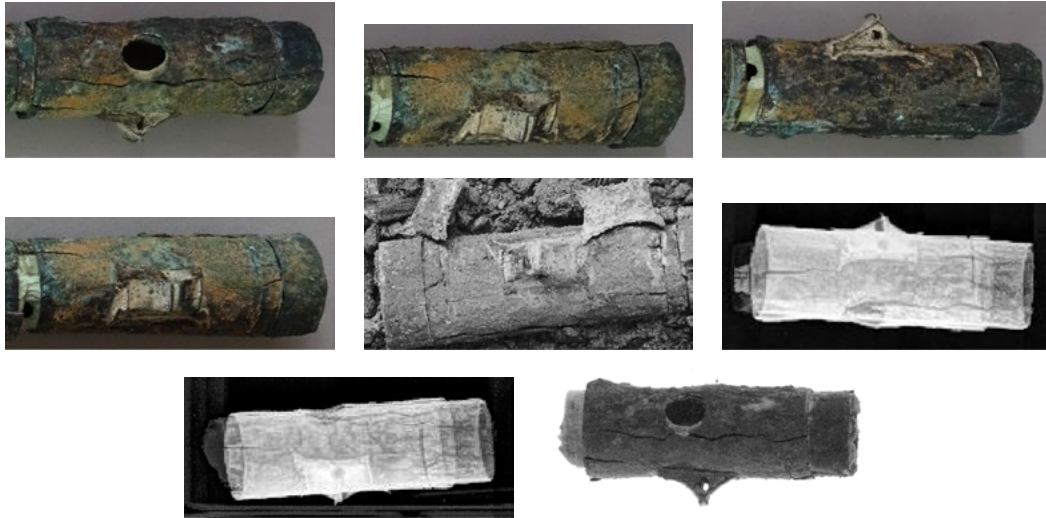
Where parts could not be measured individually, data for larger compounds are given at the end.

Images include cutouts from photographs © Museum of Fine Arts, Boston: A3050_NS, C9218-NS, C9489, C9490, C9491, C9492, XR1625, XR1627.

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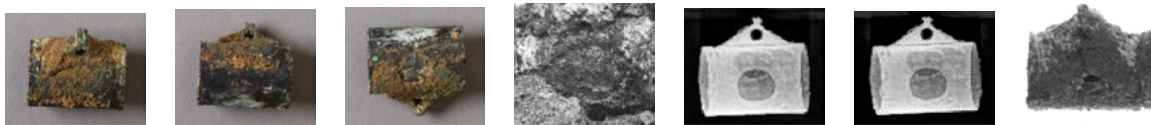
001 Tray: 01-01 Bodley: 3-14 LL-03

Measurements see compound 001, Lng=47, Di=9.3, Do=16, Cuts=1



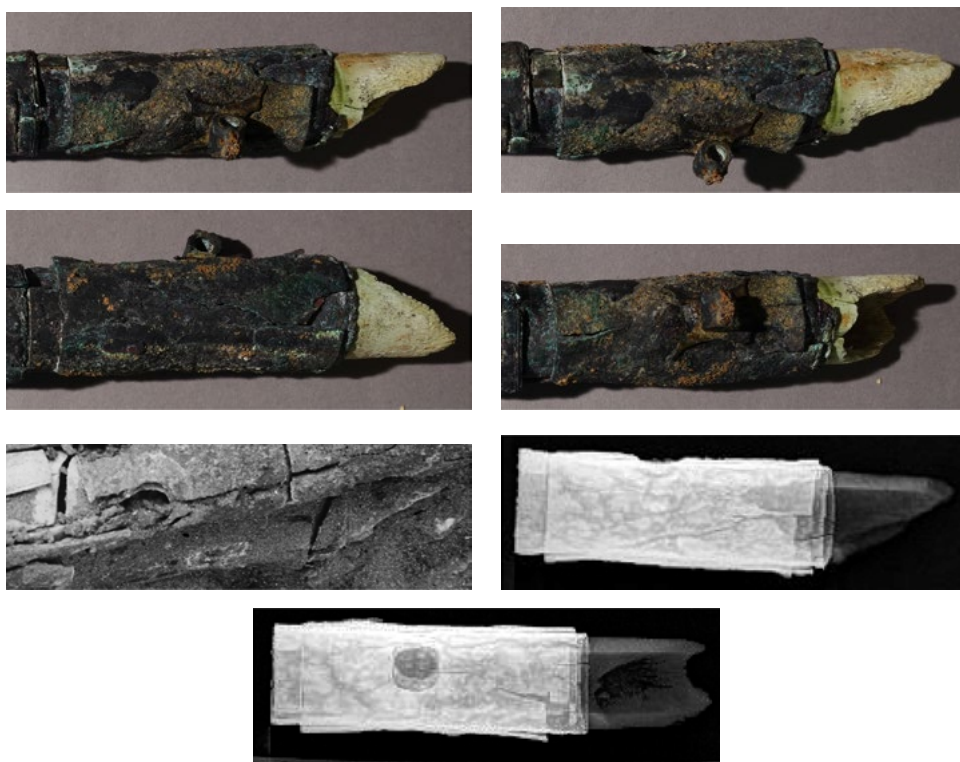
002 Tray: 01-02 Bodley: 3-12 S2-H-05

Lng=19.9, Di≈7.5, Do=14.25, H1Pos=10.3, H1Dl=6.1, H1Dt=6.2, H1Az=0, H1BAz=-100, H1BS=T, H1BPos=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.2, Cu=95.3, Sn=4.4, Pb=0.1, Cuts≈1



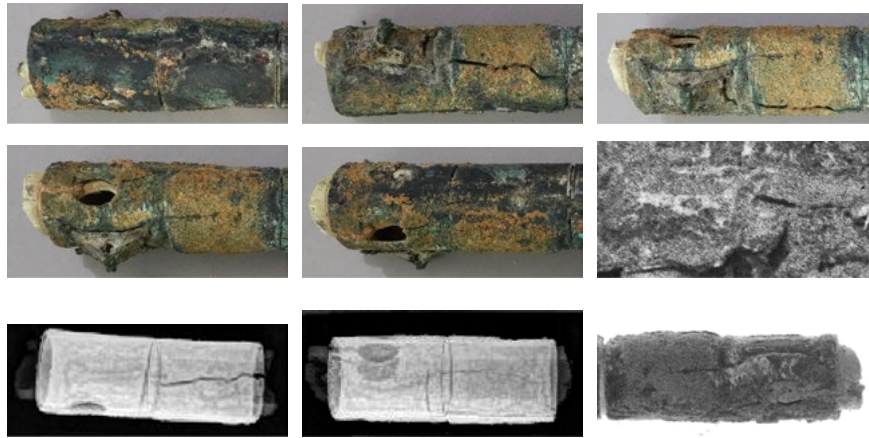
003 Tray: 01-03 Joined to: 010 HR-02

Measurements see compound 003, Lng=46.5, Di=9.15, Sp2L=20, Sp2D=14, Cuts=1



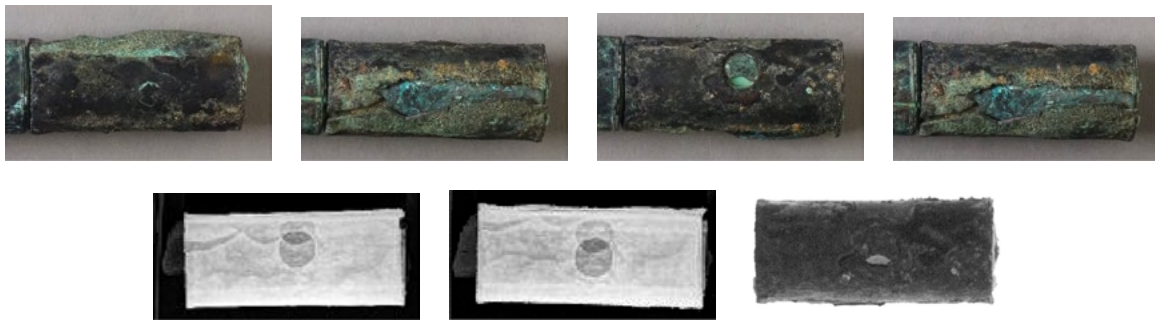
004 Tray: 01-04 Bodley: 3-12 Joined to: 114 S2-H-06

Measurements see compound 004, Lng=40, Di=7.2, Fe=0.2, Cu=99.1, Sn=0.7, Pb=0.0, Cuts=1



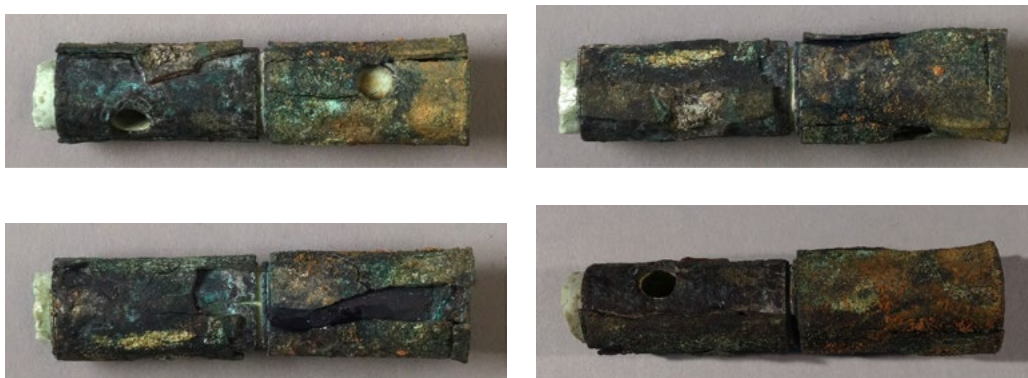
005 Tray: 01-05 Bodley: 3-05 Joined to: 024 LL-02

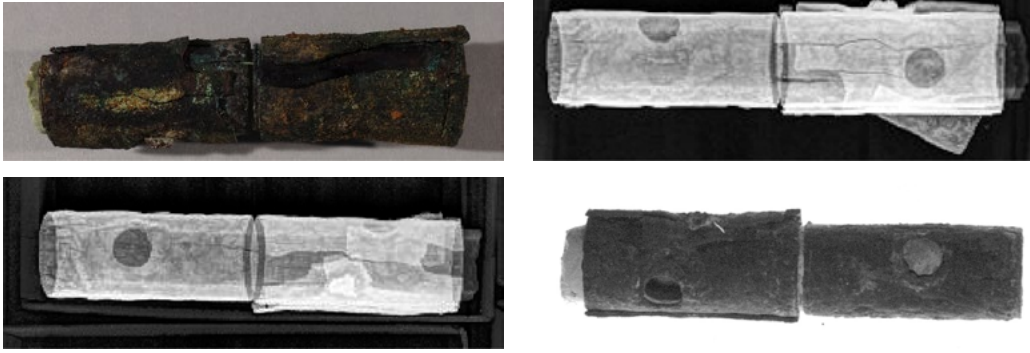
Lng=38, Di=8.7, Do=16.6, H1Pos=17.5, H1DI=5.5, H1Dt=6, H1Az=0, H1BAz=114, H1BPos=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Sct1=38



006 Tray: 01-06 Bodley: 4-04 LR-10

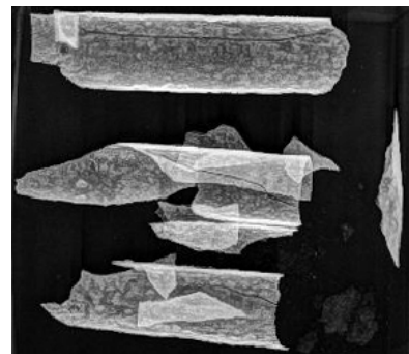
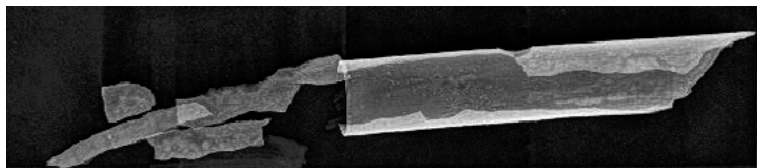
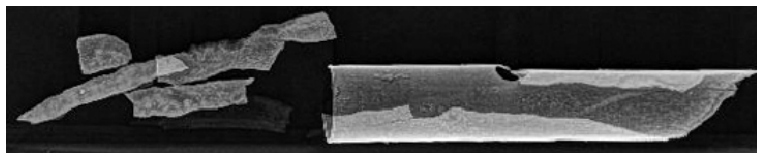
Lng=71.5, Di=8.8-8.7, Do=16, H1Pos=16.5, H1DI=7, H1Az=0, H1BAz=111, H1BPos=0, H2Pos=58.5, H2DI=7, H2Az=0, H2BS=R, H2BAz=157, H2BPos=-3, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=97.2, Sn=2.7, Pb=0.0, Sct1=38.5, Pt1=8,-80, Pt2=15.5,-80, Cuts=2





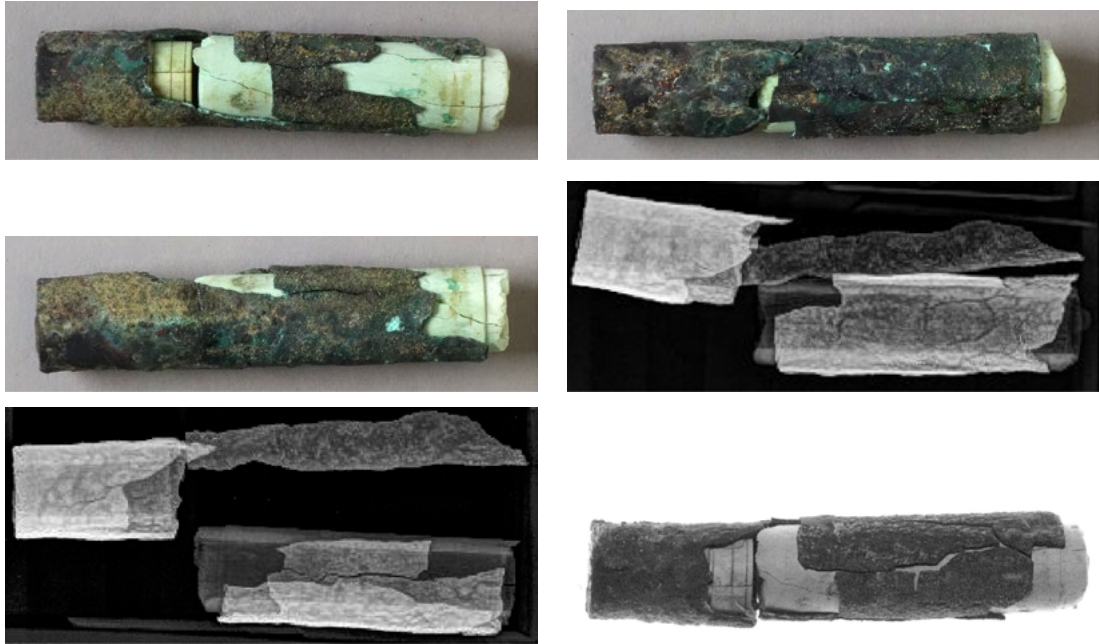
007 Tray: 01-07 Bodley: 3-07 LL-05

Lng=111.5, Di \approx 8.9, Do=16, H1Pos=74.5, H1Dl=6.5, H1Dt=6.25, H1Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.0, Cu=96.4, Sn=3.6, Pb=0.0, Pt1=73.25,0



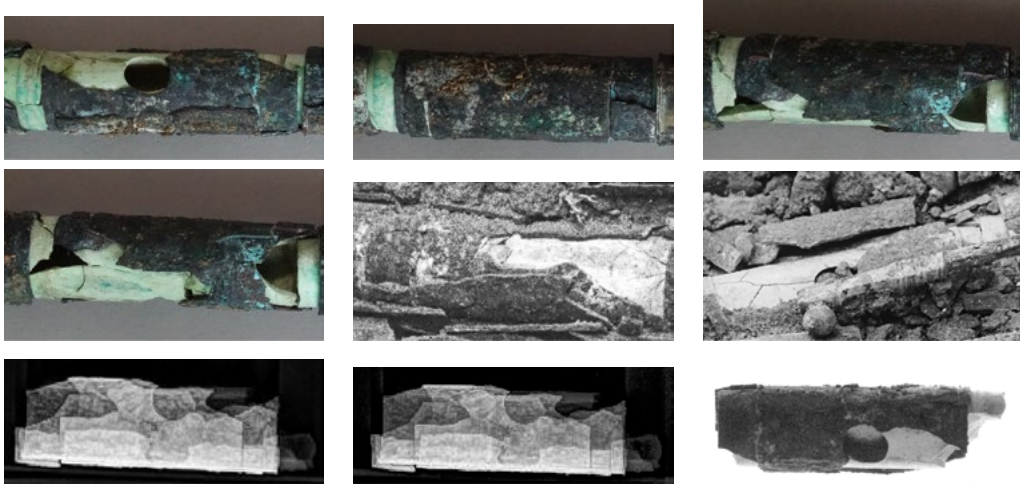
008 Tray: 01-08 Bodley: 3-09 Joined to: 005 LL-02

Lng=76, Di=9.3, Do=16, E1P=1, E1T=Sm, E2P=1, E2T=Sm



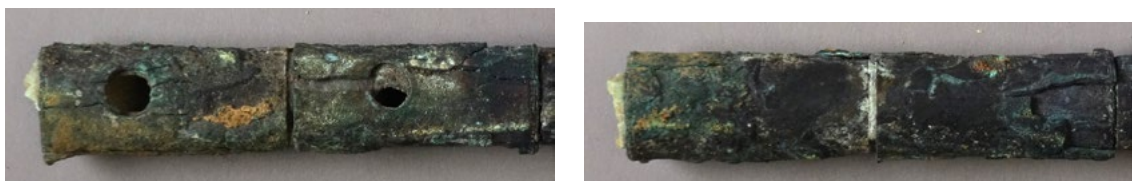
009 Tray: 01-09 Bodley: 3-10 Joined to: 098 HL-03

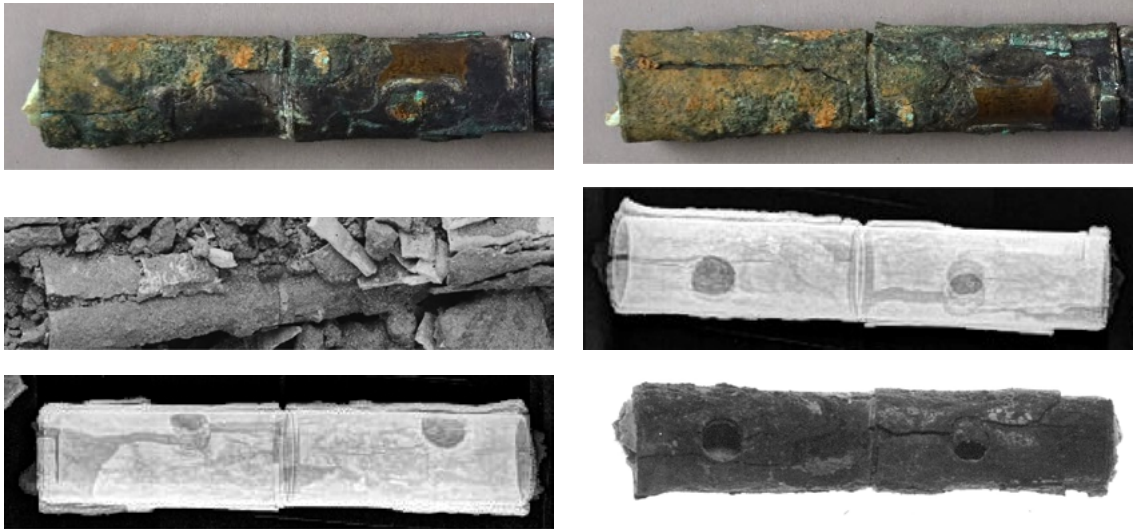
Measurements see compound 041, Lng=45.7, Di=9.7, Cuts=1



010 Tray: 01-10 Bodley: 4-07 Joined to: 003 HR-02

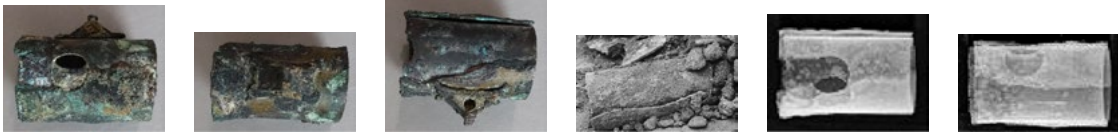
Measurements see compound 003, Lng=78.5, Di=8.65, Fe=0.0, Cu=89.9, Sn=9.4, Pb=0.7, Cuts=2





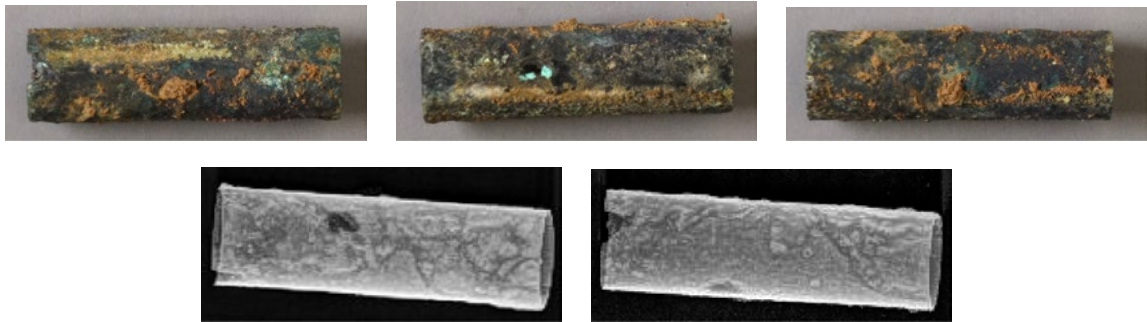
011 Tray: 01-11 S2-L-08

Lng=23, Di≈7.5, Do=14.25, H1Pos=14, H1Dl=6, H1Dt=6, H1Az=0, H1BAz=115, H1BPos=-2.5, H1BS=T, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.0, Cu=90.9, Sn=9.0, Pb=0.0



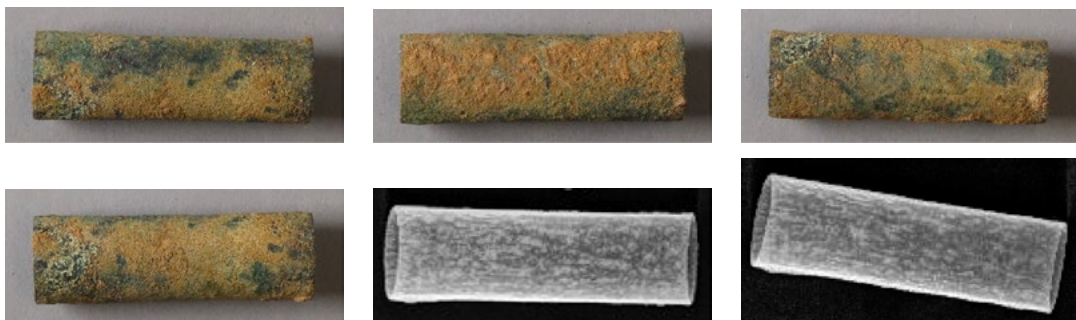
012 Tray: 01-12 W2-H-05

Lng=51.5, Do=15.5, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.0, Cu=95.3, Sn=4.7, Pb=0.0



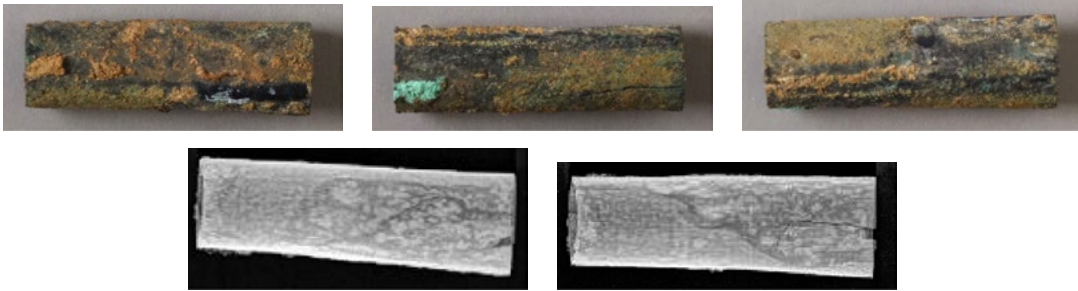
013 Tray: 01-13 S2-L-09

Lng=48.3, Do=14.25, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.3, Cu=99.4, Sn=0.3, Pb=0.0



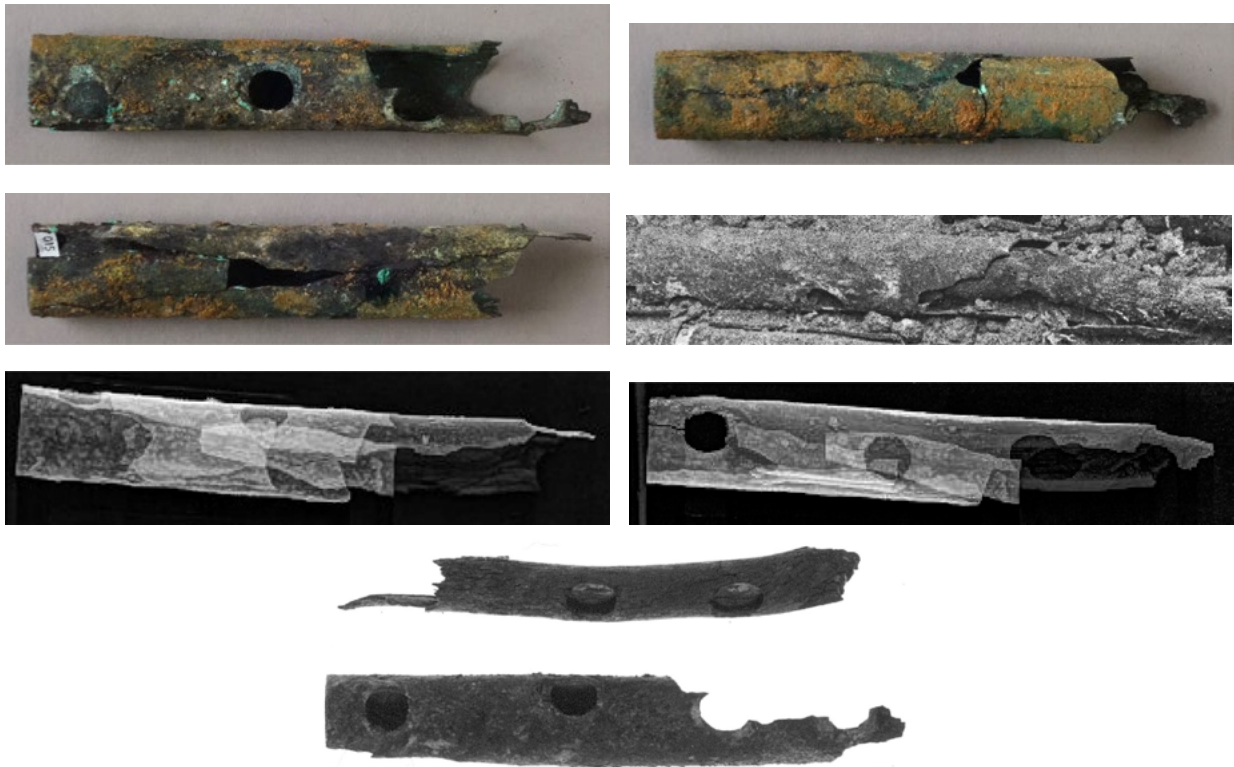
014 Tray: 01-14 W1-H-03

Lng=48.5, Do=14.5, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=89.5, Sn=10.4



015 Tray: 01-15 Bodley: 3-08 W1-H-04

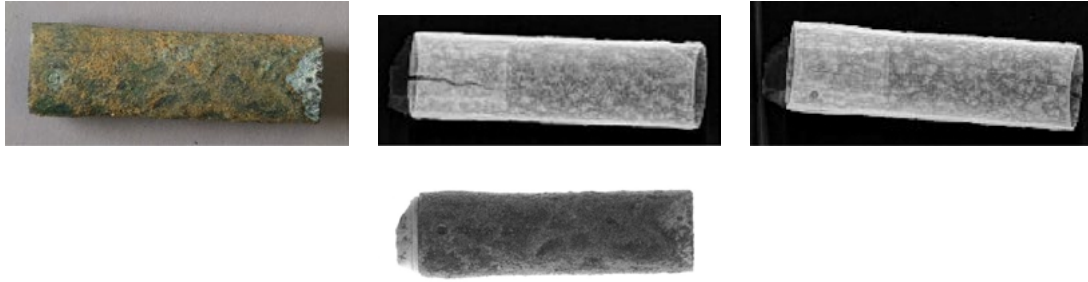
Lng=91, Do=14.5, H1Pos=10, H1DI=6.8, H1Dt=6.4, H1Az=-10, H2Pos=38.8, H2DI=7.3, H2Dt=6.5, H2Az=-20, H3Pos=62.6, H3DI=7.4, H3Dt=6.5, H3Az=0, H4Pos=76.5, H4DI≈7.4, H4Dt≈6.5, H4Az=-62, H5Pos=82.2, H5DI≈7, H5Dt≈6.5, H5Az=0, E1P=1, E1T=Sm, E2P=0, Fe=0.1, Cu=94.2, Sn=5.7



016 Tray: 02-01 Bodley: 3-02 S2-L-10

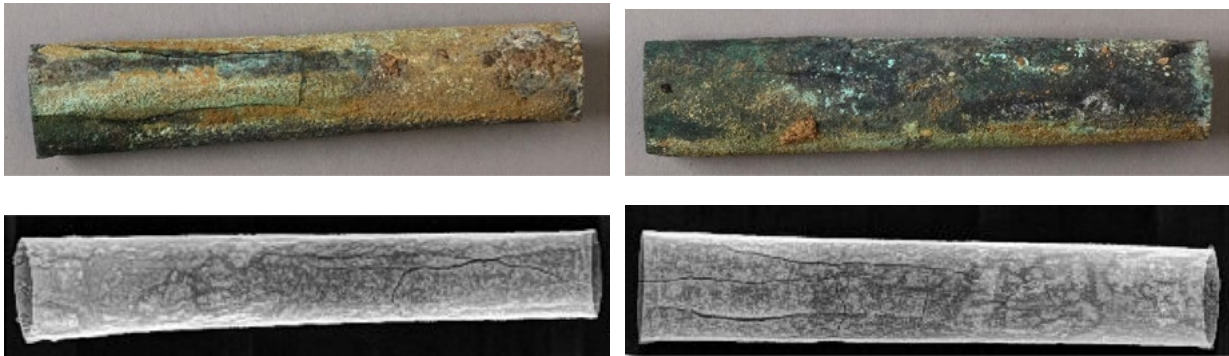
Lng=49, Do=14.25, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=5.9, Cu=91.2, Sn=2.8, Pb=0.1





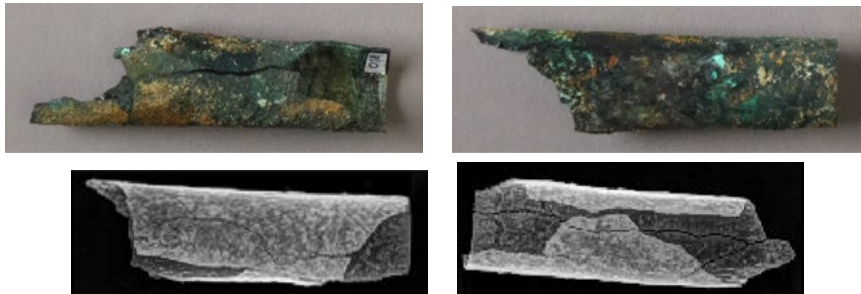
017 Tray: 02-02 LL-09

Lng=89, Do=16, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=97.4, Sn=2.5, Pb=0.0



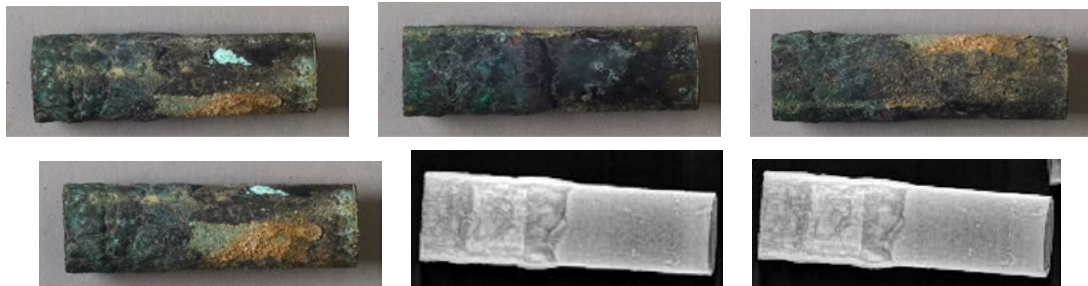
018 Tray: 02-03 W1-H-05

Lng=59.5, Do≈15, E1P=0, E1T=B, E2P=1, E2T=Sm, Fe=0.0, Cu=94.6, Sn=5.3



019 Tray: 02-04 S1-H-12

Lng=48.9, Do=14.25, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=91.0, Sn=8.9



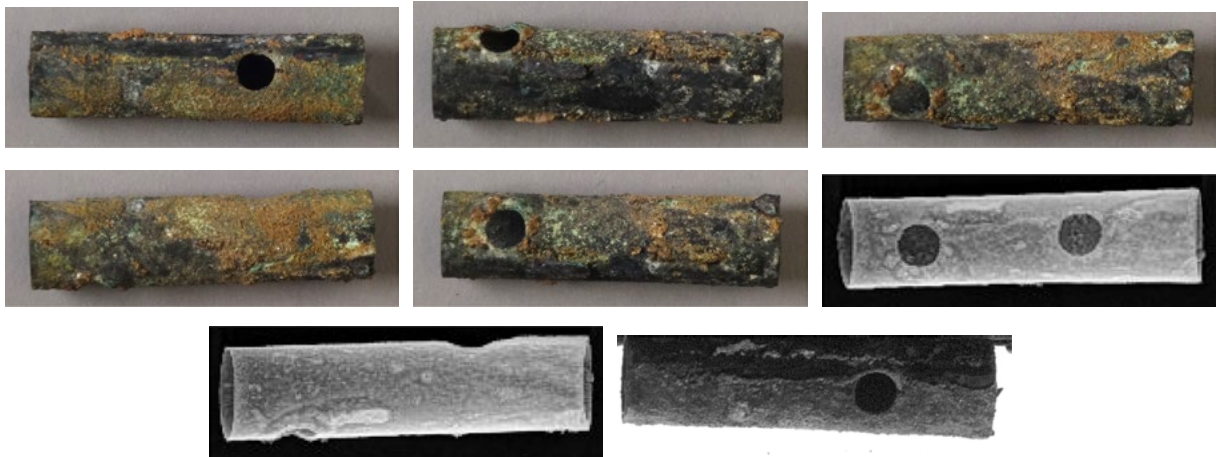
020 Tray: 02-05 S2-H-07

Lng=18.3, Do=14.25, H1Pos=8, H1Dl=7, H1Dt=5.9, H1Az=0, H1BAz=-120, H1BPos=1, H1BS=K, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.4, Cu=97.9, Sn=1.6, Pb=0.1



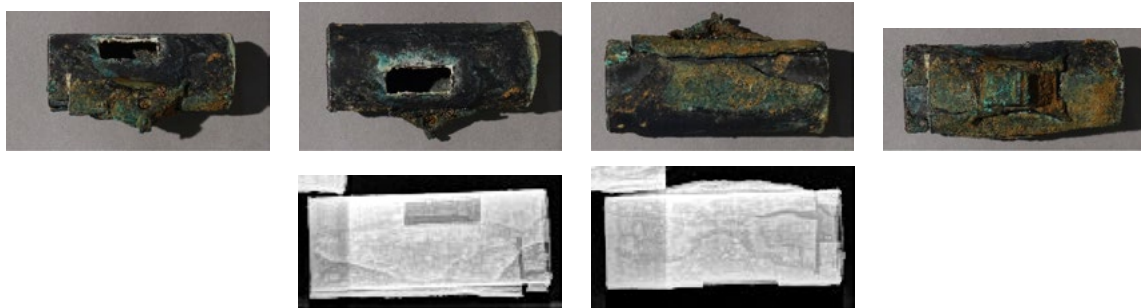
021 Tray: 02-06 Bodley: 6-03a W1-L-05

Lng=56.2, Do=14.5, H1Pos=18.3, H1Dl=6.3, H1Dt=6.3, H1Az=0, H2Pos=45.7, H2Dl=6.5, H2Dt=6.4, H2Az=175, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=97.5, Sn=2.4



022 Tray: 12-03 HR-03

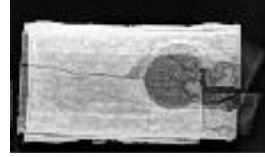
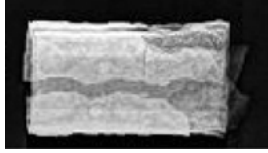
Lng=37.5, Do=16, H1Pos=15.5, H1Dl=12, H1Dt=5, H1S=R, H1Az=0, H1BAz=-107, H1BPos=3.5, H1BS=T, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Cuts=1



023 Tray: 02-08 S1-H-03

Lng=63.8, Di=7.6-7.7, Do=14.25, H1Pos=20, H1Dl=7.5, H1Dt=6.5, H1Az=0, H1BAz=130, H1BPos=-7.5, H1BS=T, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=91.4, Sn=8.5, Pb=0.1, Sct1=27.5, Cuts=1





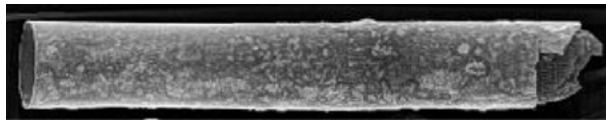
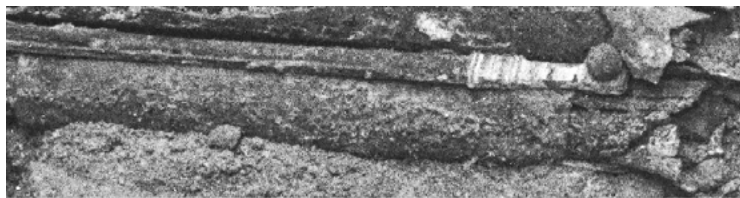
024 Tray: 02-09 Joined to: 005 LL-02

Lng=57, Di=8.9, Do=16, Fe=0.0, Cu=98.1, Sn=1.8, Pb=0.1



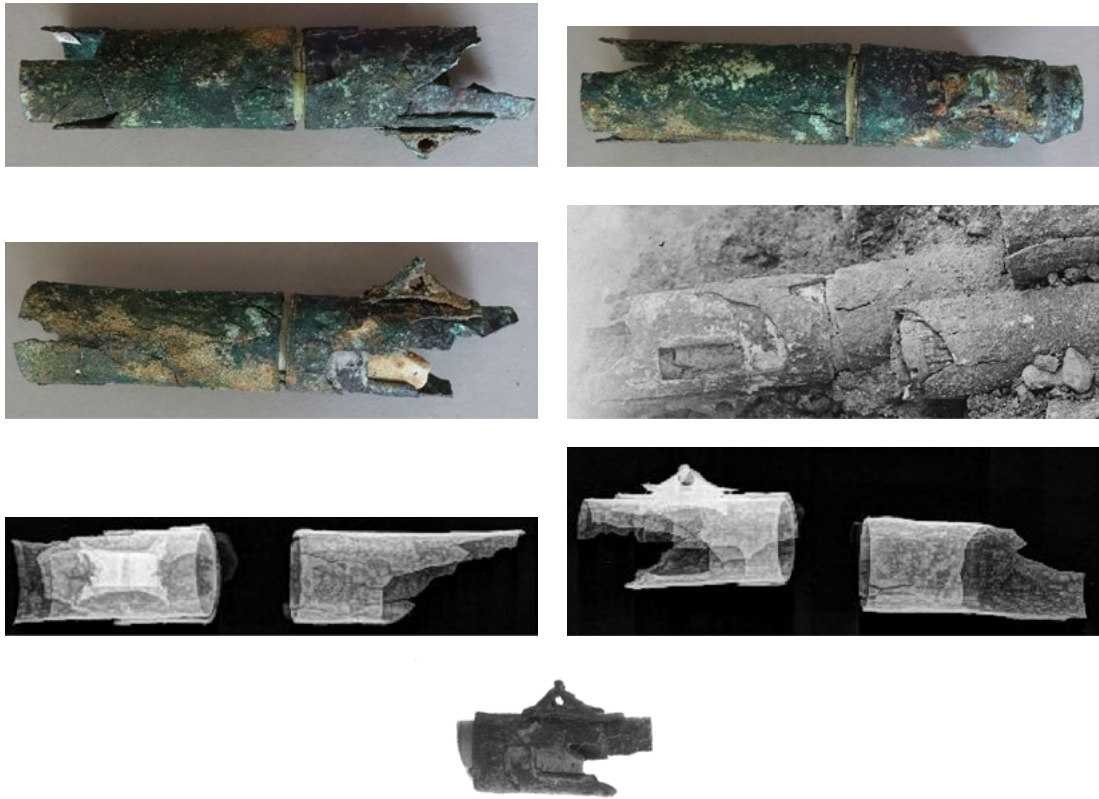
025 Tray: 02-10 W2-L-01

Lng=95.2, Do=14.5, E1P=1, E1T=Sm, E2P=0, Fe=0.1, Cu=94.5, Sn=5.4



026 Tray: 02-11 Bodley: 4-01 HL-02

Lng=76, Di=9.5-9.7, Do=16, H1Pos=58, H1DI≈11, H1Dt=5, H1S=R, H1Az=0, H1BAz=-100, H1BPos=0, H1BS=T, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Sct1=39.5, Cuts≈1



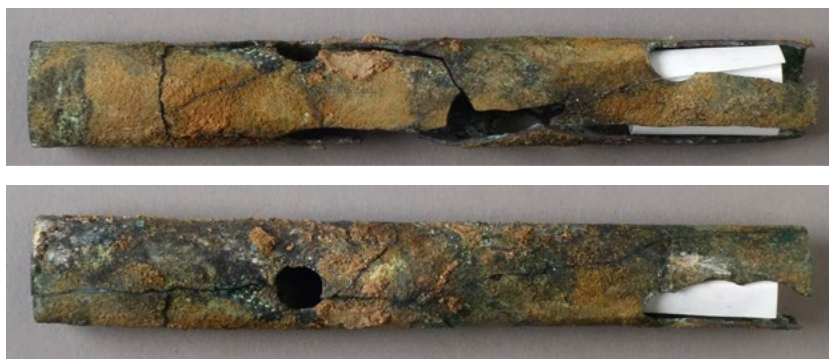
027 Tray: 02-12 LR-05

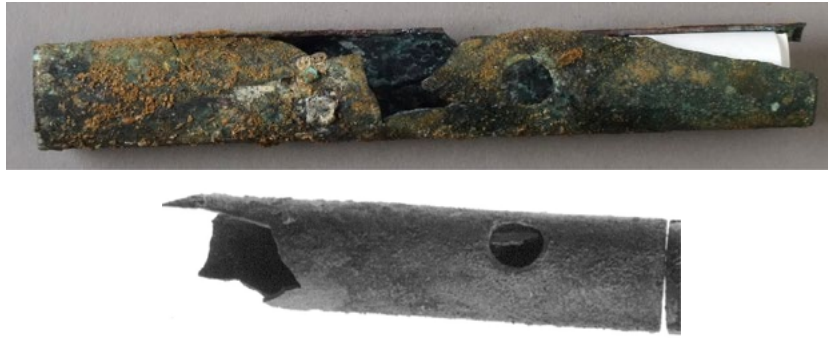
Lng=18.9, Do=16, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=94.7, Sn=4.7, Pb=0.5



028 Tray: 02-13 Bodley: 6-02d LL-08

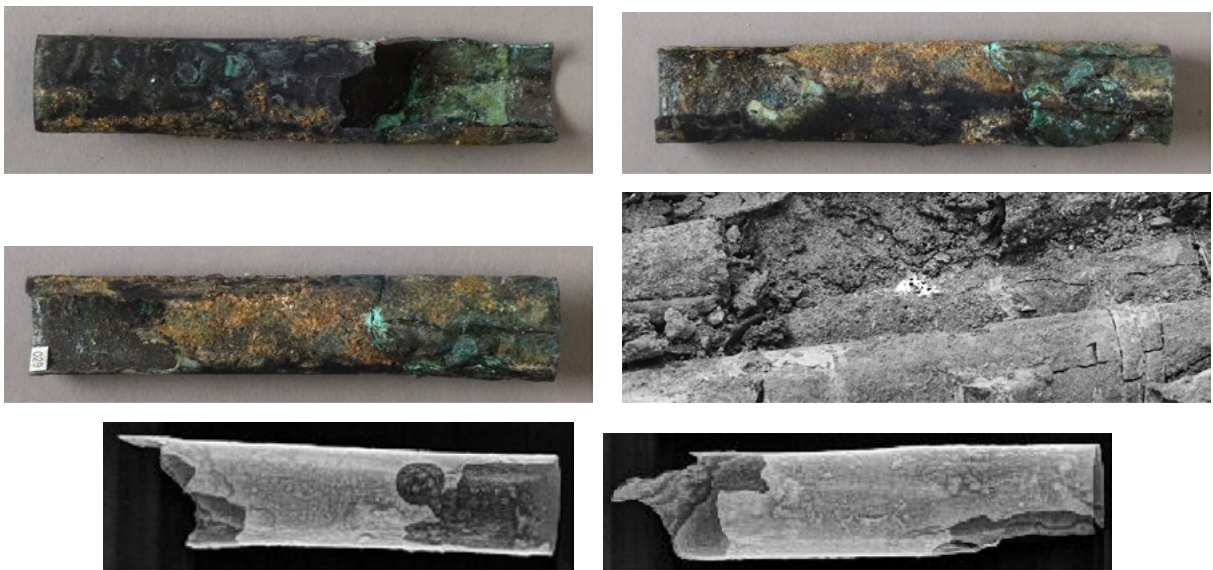
Lng=118.7, Do=16, H1Pos=22.5, H1DI=7.1, H1Dt=7.1, H1Az=0, H2Pos=44, H2DI=7.8, H2Dt=6.8, H2Az=-167, H3Pos=78.7, H3DI=7.2, H3Dt=7.1, H3Az=31, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.2, Cu=96.5, Sn=3.3, Pb=0.0





029 Tray: 02-14 Joined to: 097 HL-07

Lng=84, Do=16, H1Pos=20, H1Dl=6.9, H1Dt=6.8, H1Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=91.1, Sn=8.8, Pb=0.0



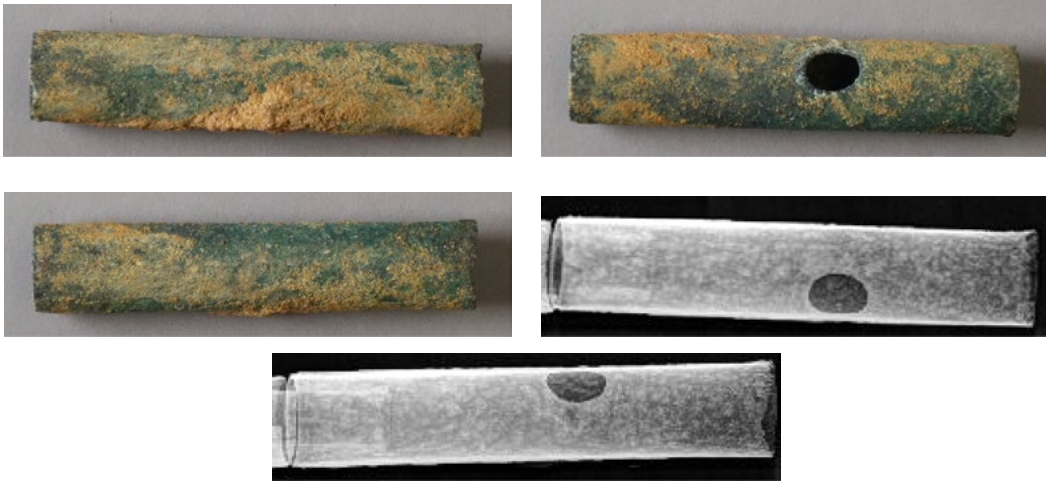
030 Tray: 02-15 S1-H-02

Lng=29.8, Di≈7.5, Do=14.25, H1Pos=12.2, H1Dl=6.4, H1Dt=6.4, H1Az=0, H1BAz=95, H1BPos=-1.5, E1P=1, E1T=Sp, Sp1L=14.3, Sp1D=11-11.5, E2P=1, E2T=Sm, Fe=0.2, Cu=97.8, Sn=1.9, Pb=0.1, Sct1=23.6, Pt1=-14.8, 0, Cuts=1



031 Tray: 02-16 S1-L-02

Lng=72.5, Di=7.2, Do=14.25, H1Pos=30.3, H1DI=8.8, H1Dt=6.7, H1Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=99.0, Sn=0.9, Pb=0.0



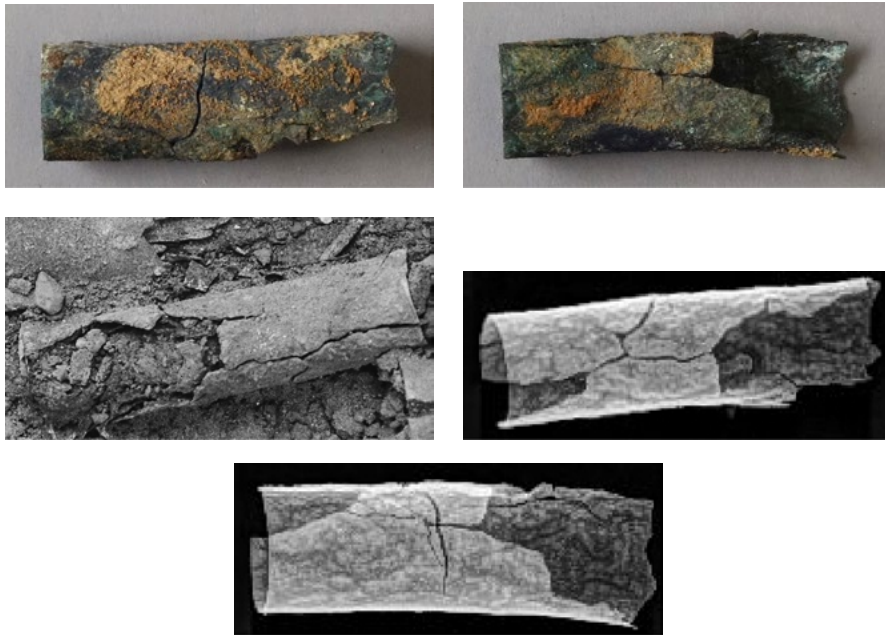
032 Tray: 02-17 Bodley: 3-01 HL-09

Lng=214.5, Do=16, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.0, Cu=95.2, Sn=4.8, Pb=0.0, Pt1=-54.2,0, Pt2=-48.35,0, Pt3=282,180



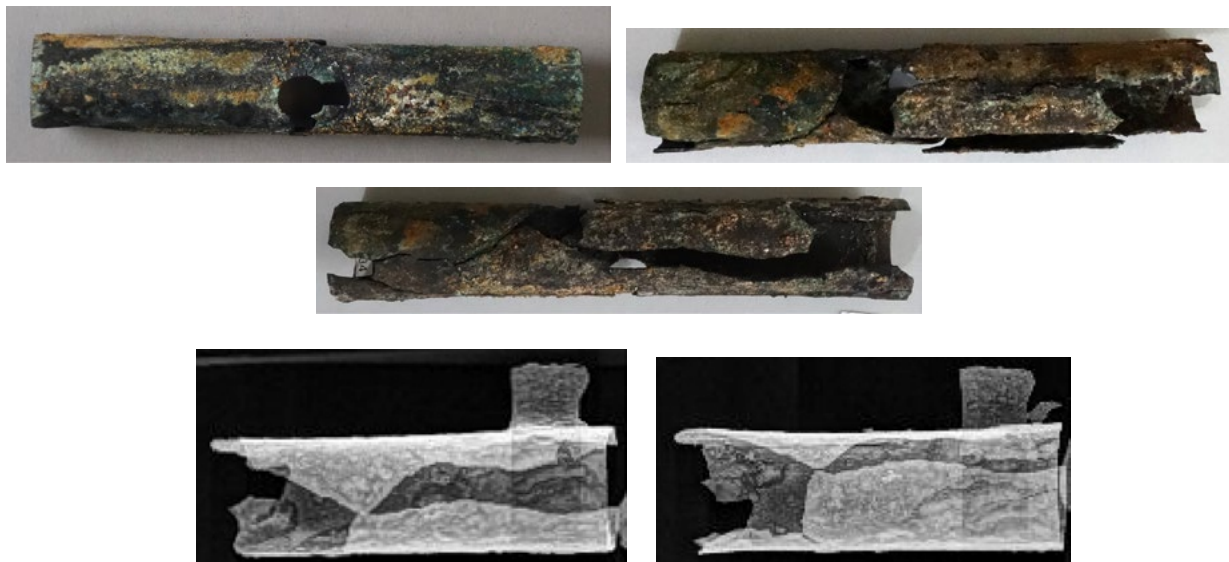
033 Tray: 02-18 HL-01

Lng=61.2, Do=16, E1P=0, E1T=B, E2P=1, E2T=Sm, Fe=0.2, Cu=96.5, Sn=3.3



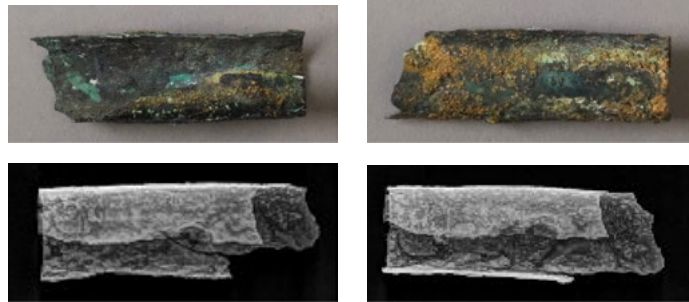
034 Tray: 02-19 HL-11

Lng=98.3, Do=16, H1Pos=12.1, H1Dl≈8, H1Dt≈7, H1S=T, H1Az=169, H1DIT≈12, H2Pos=48.3, H2Dl=8.4, H2Dt=7, H2Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=96.9, Sn=2.9, Pb=0.1



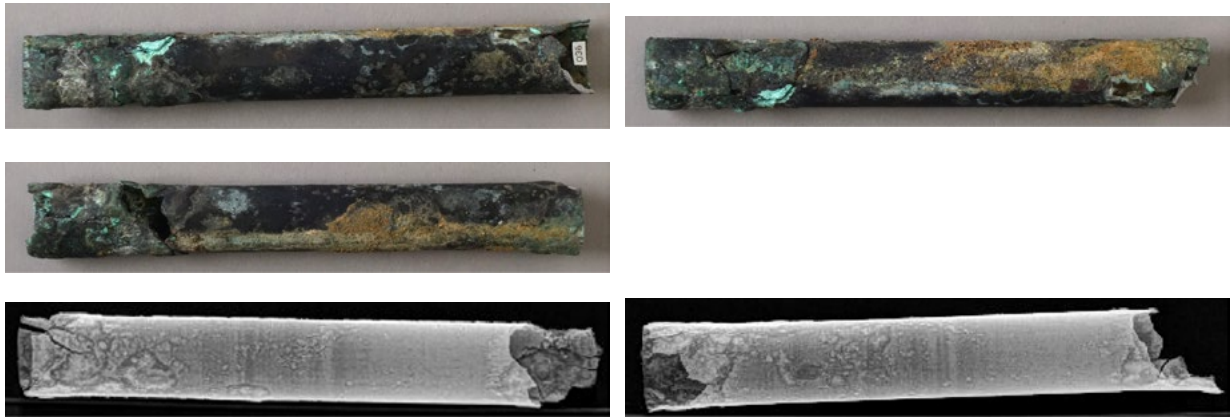
035 Tray: 02-20 W2-L-05

Lng=47, Do=14.25, E1P=0, E2P=1, E2T=Sm, Fe=0.1, Cu=97.2, Sn=2.7



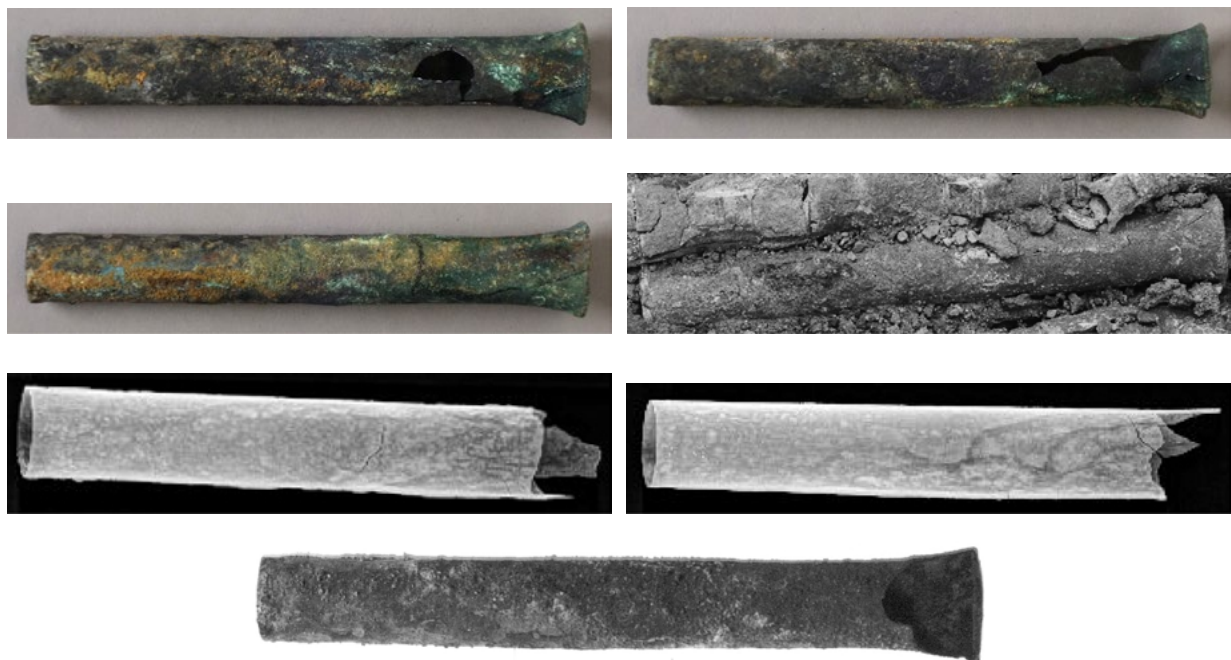
036 Tray: 02-21 LR-06

Lng=130.7, Do=16, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.3, Cu=90.2, Sn=9.5, Pb=0.1, Pt1=-54.5,176, Pt2=-50.04,176, Pt3=-56.7,176, Pt4=-51.7,184, Pt5=-47.24,184, Pt6=-53.9,184



037 Tray: 02-22 Bodley: 5-01 S1-L-01

Lng=118, Do=14.5, E1P=1, E1T=B, E2P=1, E2T=Sm, Fe=0.0, Cu=96.5, Sn=3.5



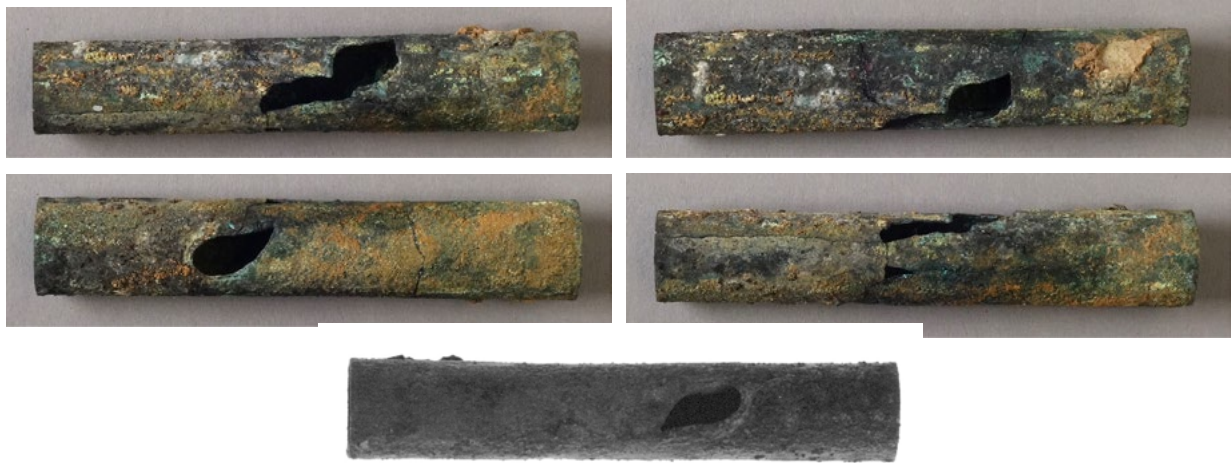
038 Tray: 02-23

Lng=17.6, Do=14.2-16.5, E1P=0, E2P=1, E2T=R, Sct1=2.4



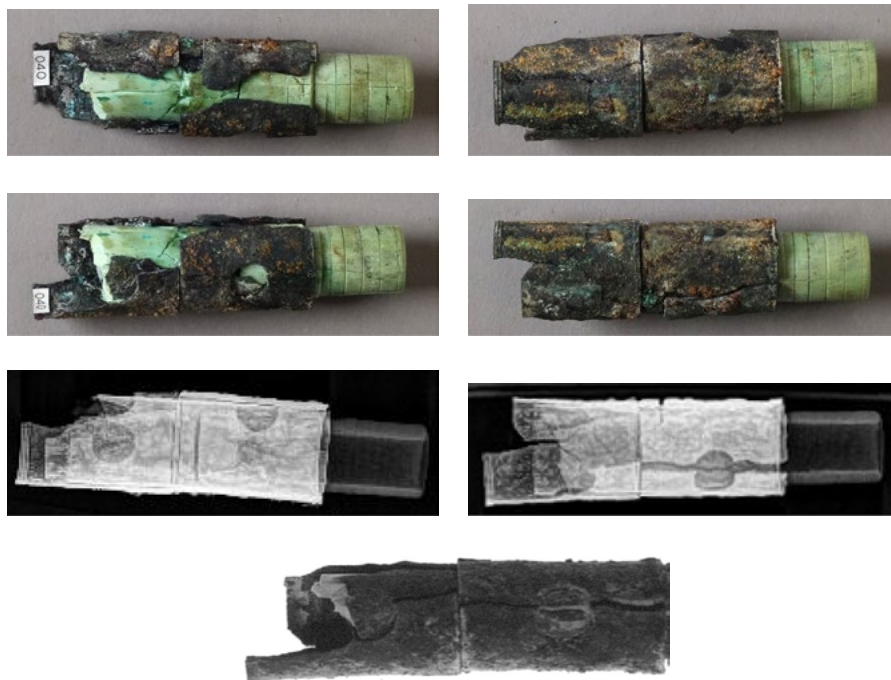
039 Tray: 03-01 Bodley: 4-08 HR-11

Lng=90, Do=16, H1Pos=30, H1DI≈7.2, H1Dt=6.4, H1S=T, H1Az=-158, H1DIT=13, H2Pos=53.5, H2DI=8.2, H2Dt=7.3, H2Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.3, Cu=91.8, Sn=7.8, Pb=0.1



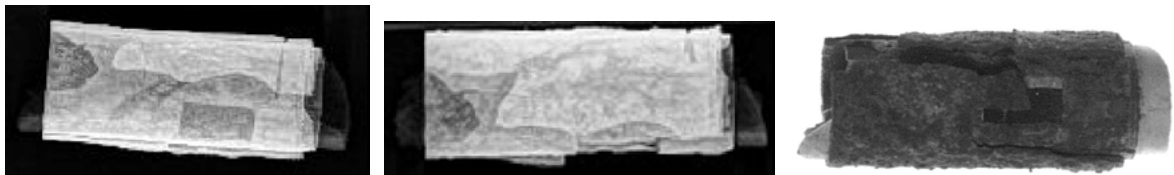
040 Tray: 03-02 Bodley: 4-02 S1-L-03

Lng=46.4, Di=7.3, Do=14.25, H1Pos=11.2, H1DI=6, H1Dt=6, H1Az=0, H1BAz=115, H1BPos=1, H1BS=T, H2Pos=32.7, H2DI=6.5, H2Dt=6.5, H2Az=0, H2BAz=115, H2BPos=1.5, H2BS=T, E1P=1, E1T=Sp, Sp1L=15.2, Sp1D=11.6, E2P=1, E2T=Sm, Fe=0.1, Cu=97.8, Sn=1.9, Pb=0.2, Sct1=22, Cuts=2



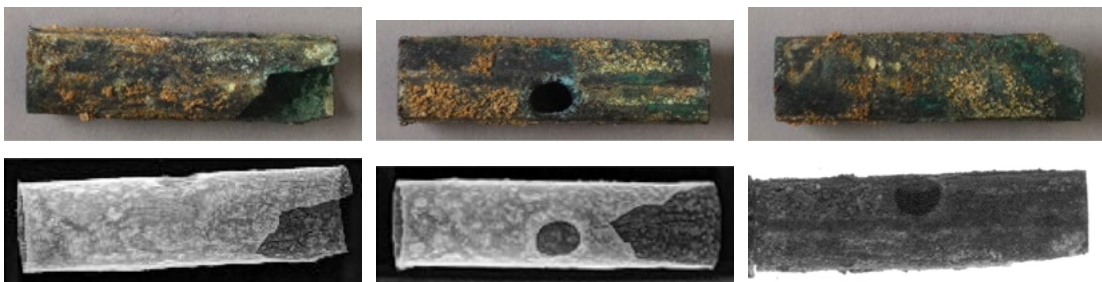
041 Tray: 03-03 Bodley: 4-15 Joined to: 009 HL-03

Measurements see compound 041, Lng=43.8, Di=9.6, Sp1L=19.5, Sp1D≈13, Cuts=1



042 Tray: 03-04 Bodley: 4-02 W1-L-03

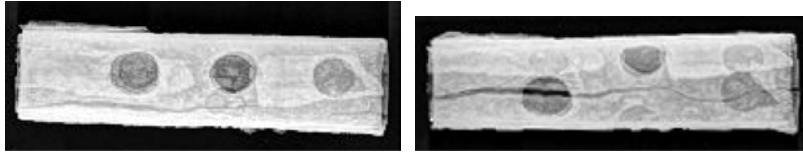
Lng=51, Do=14.5, H1Pos=25, H1Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=95.2, Sn=4.7



043 Tray: 03-05 Bodley: NP-3 S1-L-07

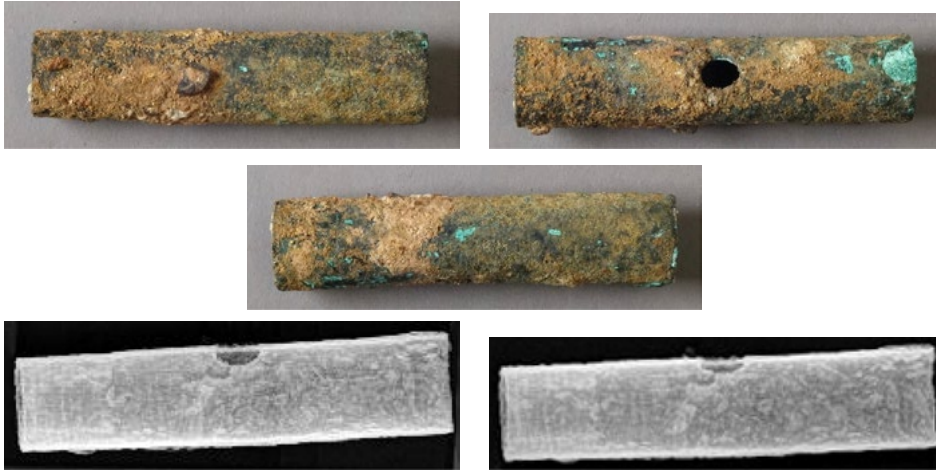
Lng=56.4, Do=14.25, H1Pos=7, H1Dl=6.1, H1Dt=5.6, H1Az=0, H1EAz=155, H2Pos=23, H2Dl=6.2, H2Dt=5.9, H2Az=0, H2BAz=-133, H2BPos=-2.5, H2BS=T, H3Pos=38, H3Dl=7.1, H3Dt=6.4, H3Az=0, H3EAz=155, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=89.1, Sn=10.9, Pb=0.0





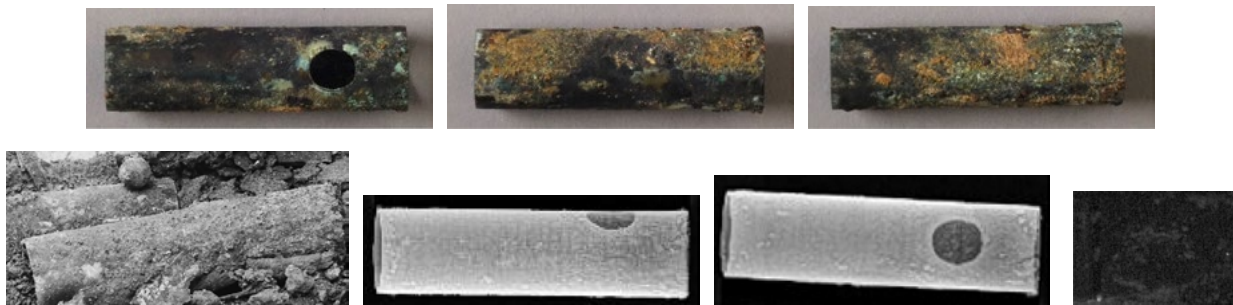
044 Tray: 03-06 S2-L-03

Lng=65, Di≈7.5, Do=14.25, H1Pos=32, H1Dl=6.4, H1Dt=5.2, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.2, Cu=99.3, Sn=0.5, Pb=0.0



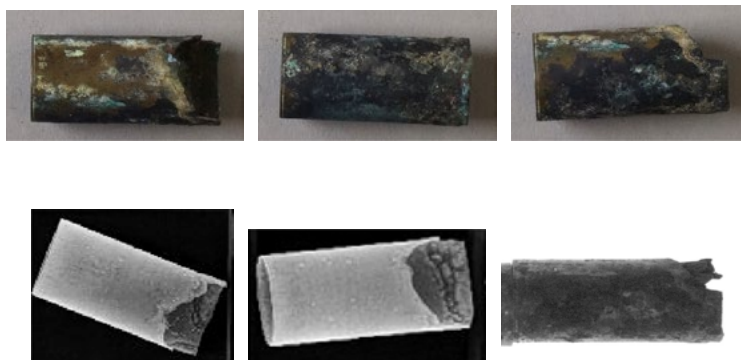
045 Tray: 03-07 Bodley: 6-02c W2-L-03

Lng=49.4, Do=14.5, H1Pos=37.2, H1Dl=7.7, H1Dt=6.8, H1Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=96.5, Sn=3.4



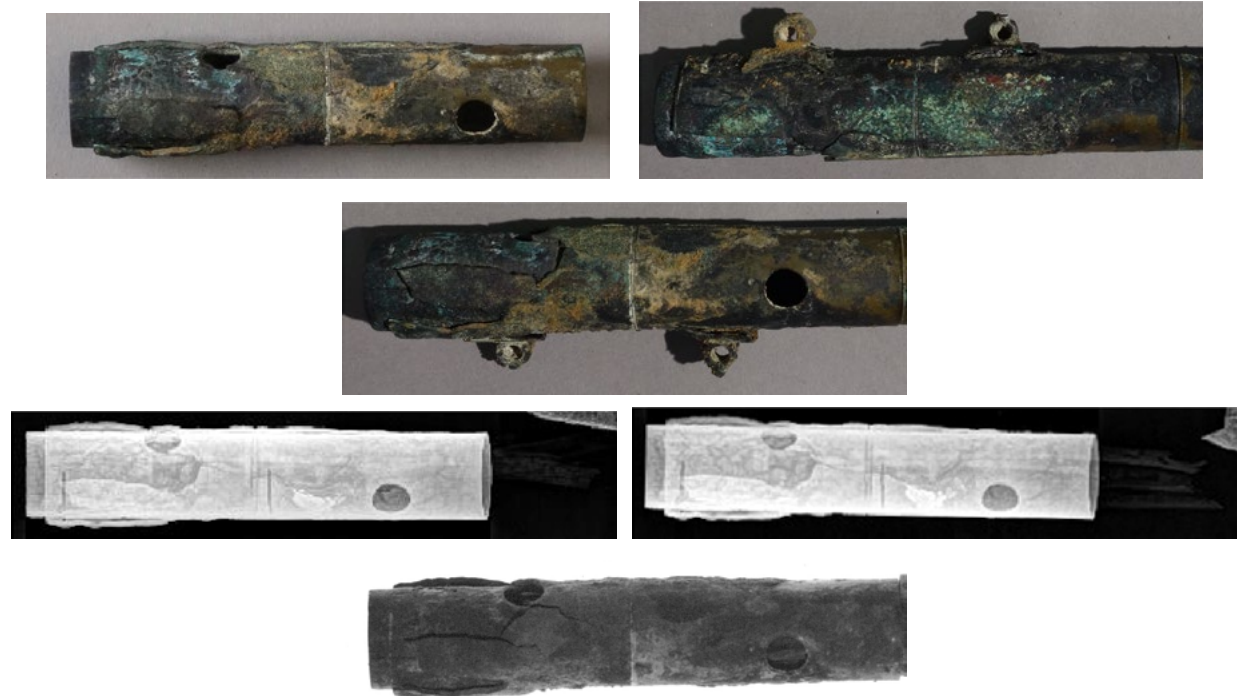
046 Tray: 03-08 Bodley: 4-10 Joined to: 047 LR-03

Lng=34, Do=16, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.7, Cu=84.4, Sn=14.7, Pb=0.1



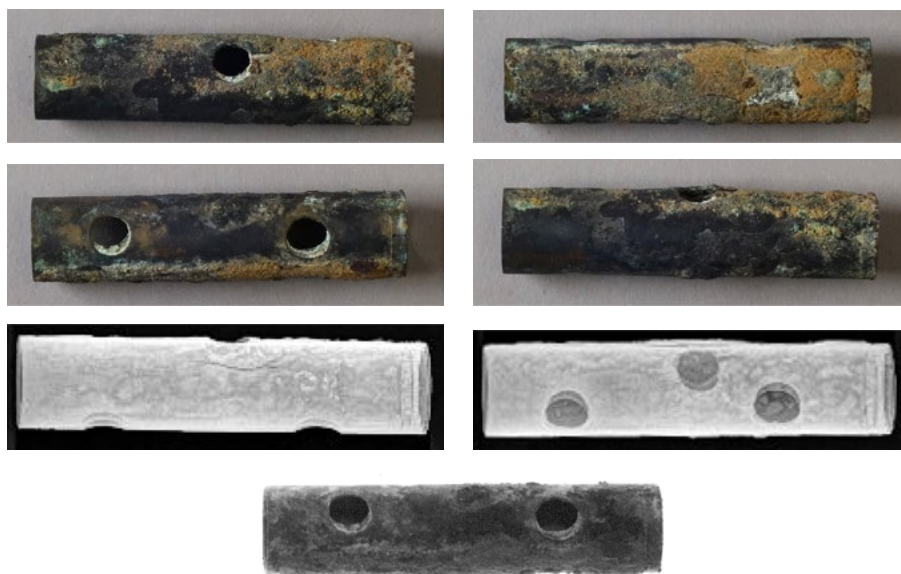
047 Tray: 03-09 Bodley: 4-10 Joined to: 046 LR-03

Lng=80.5, Di=8.7, Do=16, H1Pos=17.2, H1DI=6, H1Dt=6.05, H1Az=-89, H1BAz=-91, H1BPos=5, H1BS=R, H2Pos=57, H2DI=6.2, H2Dt=6.4, H2Az=0, H2BAz=165, H2BPos=-2, H2BS=R, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.0, Cu=90.2, Sn=9.8, Pb=0.0, Sct1=77, Sct2=40.5, Pt1=39.95,0, Cuts=2



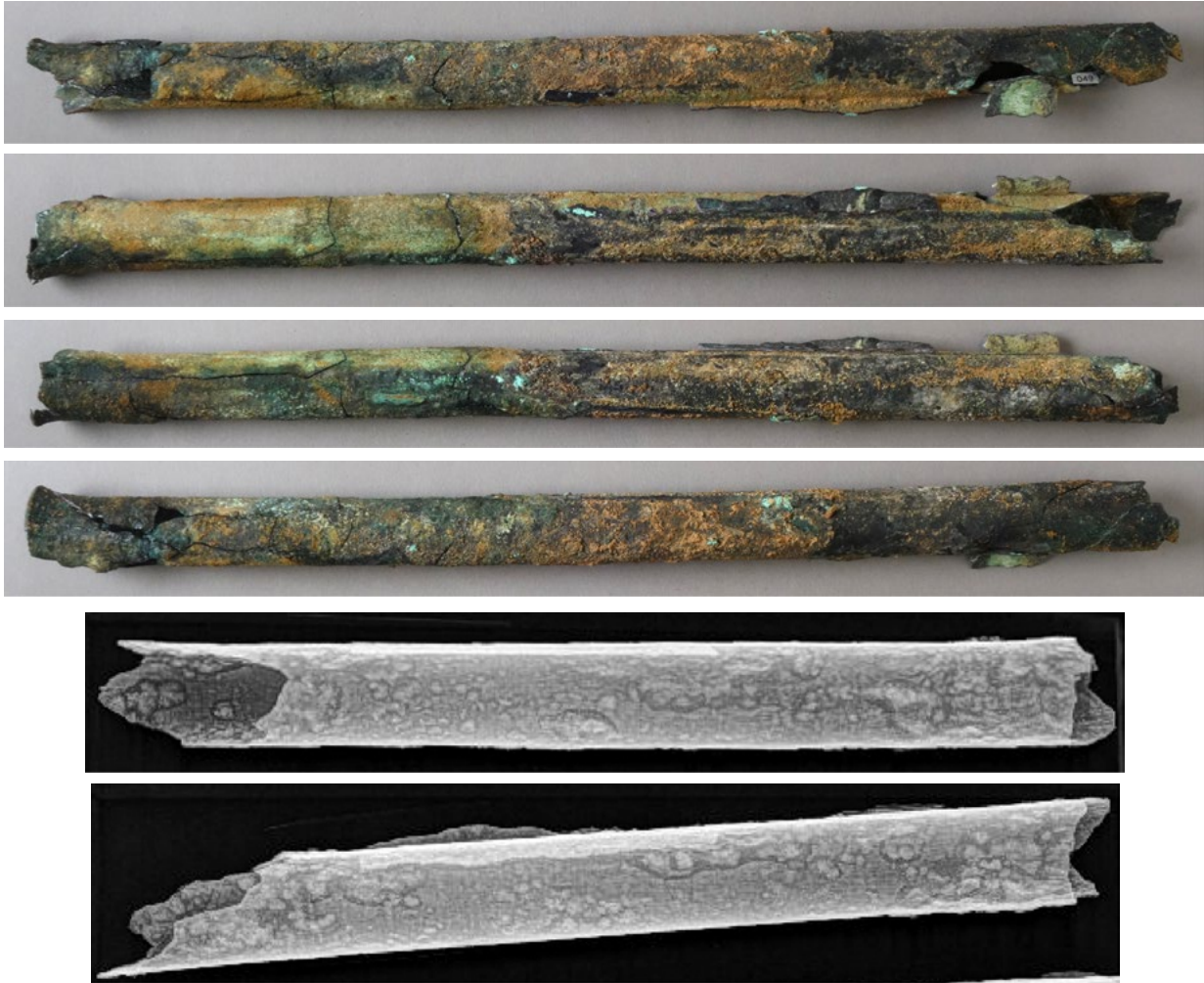
048 Tray: 03-10 Bodley: 3-04 S1-H-11

Lng=62.4, Do=14.25, H1Pos=16.9, H1DI=6.8, H1Dt=6.4, H1Az=-10, H1BAz=-90, H1BPos=3, H1BS=K, H2Pos=30.2, H2DI=6.2, H2Dt=6.8, H2Az=160, H3Pos=49.4, H3DI=6.5, H3Dt=6.4, H3Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=90.9, Sn=9.0, Pb=0.1



049 Tray: 03-11 LR-01

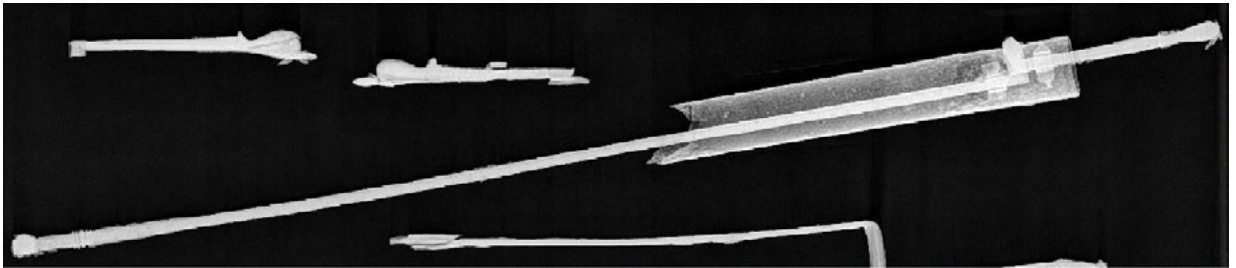
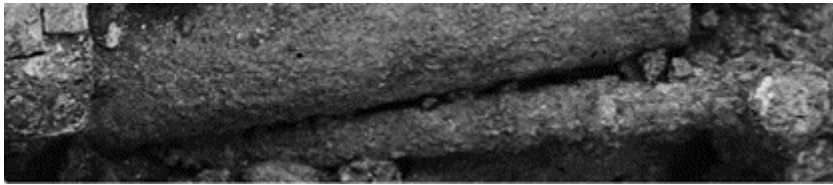
Lng=272, Do=16, E1P=1, E1T=B, E2P=1, E2T=Sm, Fe=0.1, Cu=94.1, Sn=5.8, Pb=0.0



050 Tray: 03-12 Bodley: 6-01 HR-07

Lng=132, Di=8.7, Do=16, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=89.6, Sn=10.2, Pb=0.1, Pt1=-47.0, Pt2=-53.05,0, Pt3=-46.85,0, Pt4=290.8,180, Pt5=293.7,180, Pt6=285.5,180





051 Tray: 03-13

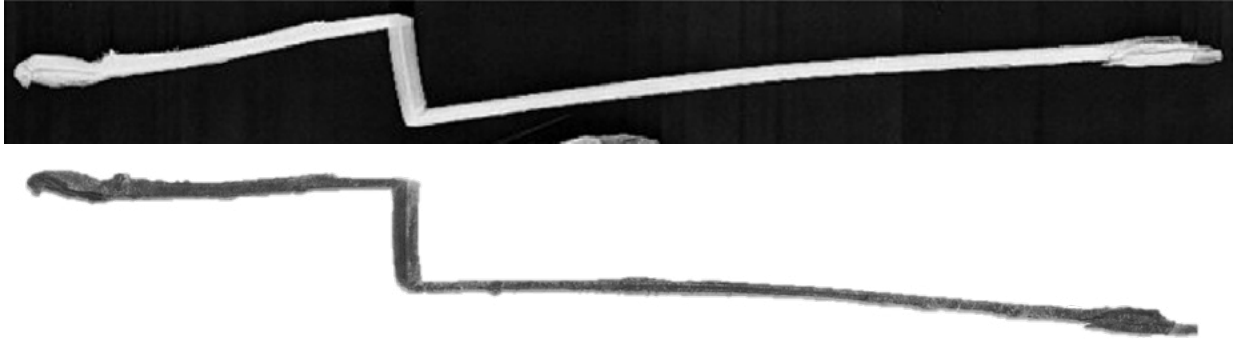
Lng=107.3



052 Tray: 03-14 Bodley: 5-14

Lng=200





053 Tray: 03-15 Bodley: 5-13
Lng=68



054 Tray: 03-16 Bodley: 5-12 Joined to: 032
Lng=58



116 — MUSIC FROM ANCIENT MEROË

055 Tray: 03-17 Bodley: 6-01

Lng=19, Di≈7.2, Do=14.2-17, Sct1=3.8, E1P=0, E2P=1, E2T=R



056 Tray: 03-18 Bodley: 6-01

Lng=16, Do≈19.5



057 Tray: 05-01 S1-H-10

Lng=25.8, Do=14.25, H1Pos=17, H1DI=6.6, H1Dt=6.2, H1Az=0, H1BAz=-119, H1BPos=-4.1, H1BS=T, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=93.3, Sn=6.6, Sct1=23.2, Cuts=1



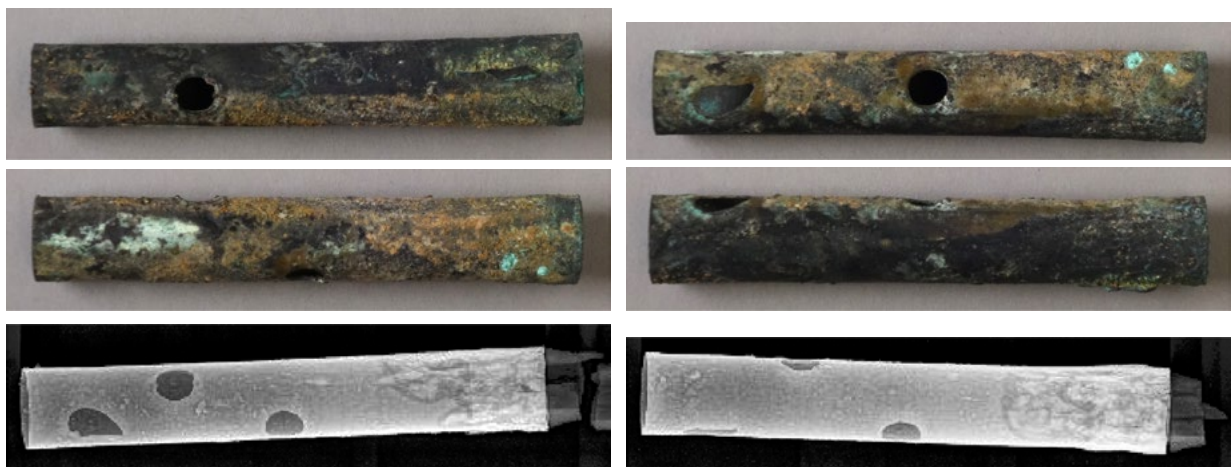
058 Tray: 05-02

Lng=16.7



059 Tray: 06-01 Bodley: 5-09 W2-H-04

Lng=90.3, Do=14.5, H1Pos=10, H1DI=6, H1Dt=5.1, H1S=T, H1Az=20, H2Pos=27, H2DI=6.3, H2Dt=5.85, H2Az=-160, H3Pos=45, H3DI=6.5, H3Dt=6, H3Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.2, Cu=90.3, Sn=9.6, H1DIT=9.2





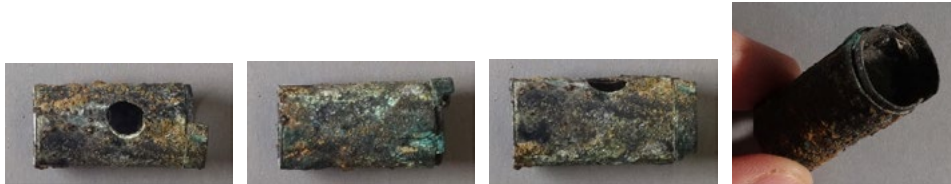
060 Tray: 06-02 W2-H-03

Lng=51, Do=14.5, H1Pos=30.5, H1DI=6.6, H1Dt=6.5, H1Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=90.3, Sn=9.6



061 Tray: 06-03 HL-08

Lng=32.5, Do=16, H1Pos=17.2, H1DI=7.05, H1Dt=6.5, H1Az=0, H1BAz=-145, H1BPos=-3, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Sct1=28.5, Fe=0.2, Cu=89.5, Sn=10.3, Pb=0.1



062 Tray: 06-04 S2-H-04

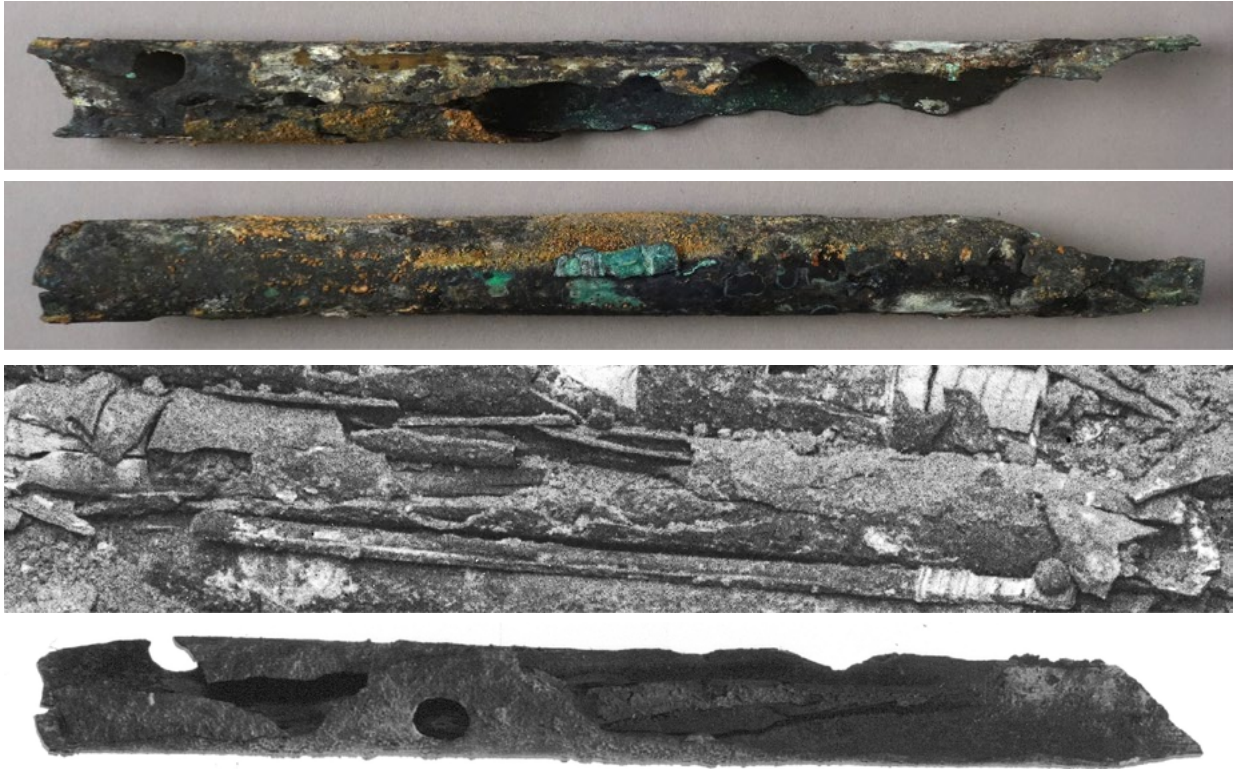
Lng=51.6, Do=14.25, H1Pos=22.6, H1DI=6.9, H1Dt=6.1, H1Az=0, H1BAz=115, H1BPos=0, H2Pos=41, H2DI=7.1, H2Dt=6.8, H2Az=0, H2BAz=115, H2BPos=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=94.7, Sn=5.1, Pb=0.1, Sct1=32.4, Sct2=15, Cuts=2, Di≈7.5, H1BS=T, H2BS=T, Sct1Pos=32.4, Sct2Pos=15, Label=L



063 Tray: 06-05 Bodley: 5-16 LR-11

Lng=184, Do=16, H1Pos=1.5, H1DI=7.3, H1Dt=7.3, H1Az=28, H2Pos=20.8, H2DI=7.95, H2Dt=7, H2Az=-150, H3Pos=59.8, H3DI=8.1, H3Dt=6.8, H3Az=0, E1P=0, E2P=1, Fe=0.1, Cu=98.1, Sn=1.7, Pb=0.0



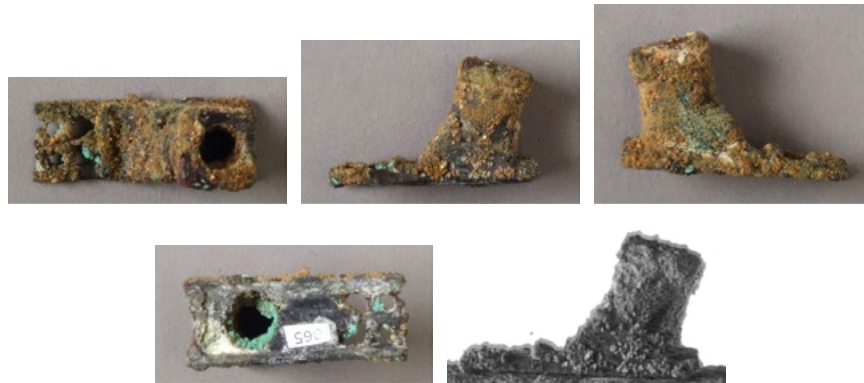


064 Tray: 06-06 W2-L-06

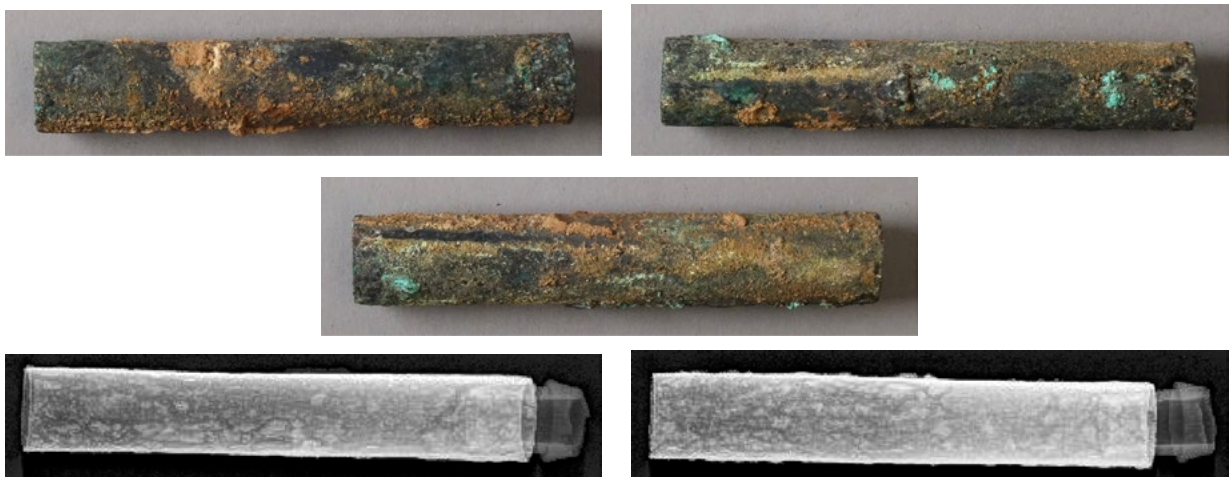
Lng=50.2, Di=7.8, Do=14, Sp1L=13.5, Sp1D=11.5, Sp2L=6.2, Sp2D=10.5



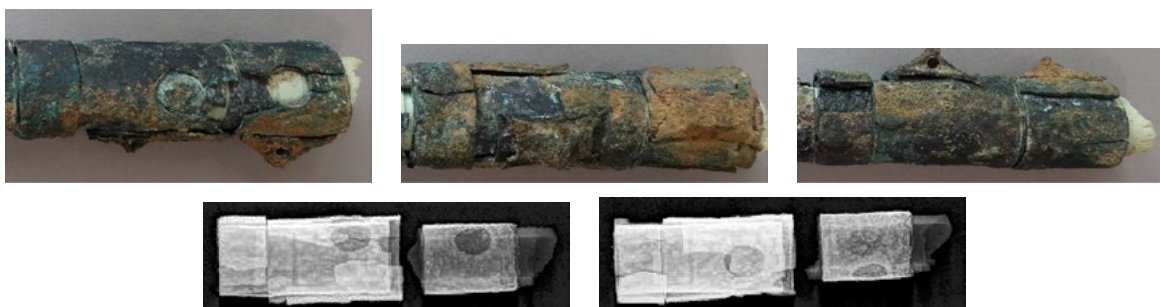
065 Tray: 06-07 Bodley: 5-09(?) Joined to: 131 HR-10
 Lng=39.7



066 Tray: 10-01 S1-L-10
 Lng=85.3, Do=14.25, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=96.1, Sn=3.9

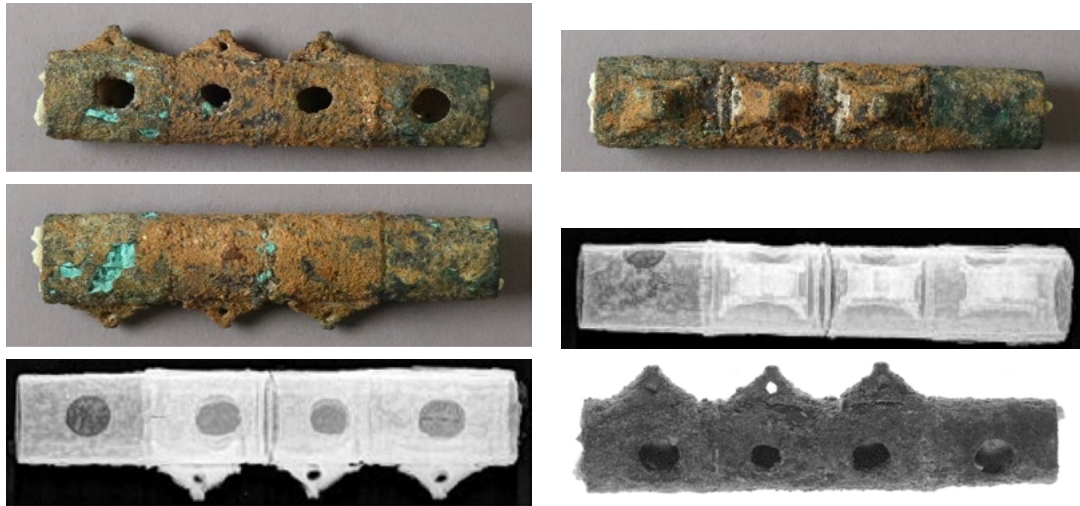


067 Tray: 10-02 Joined to: 080 S2-L-05
 Measurements see compound 067, Lng=52.3, Di=7.6, Fe=0.05, Cu=98.2, Sn=1.7, Pb=0.05, Fe1=0.1, Cu1=98.3, Sn1=1.5, Pb1=0.1, Fe2=0.0, Cu2=98.1, Sn2=1.9, Pb2=0.0, Cuts=1



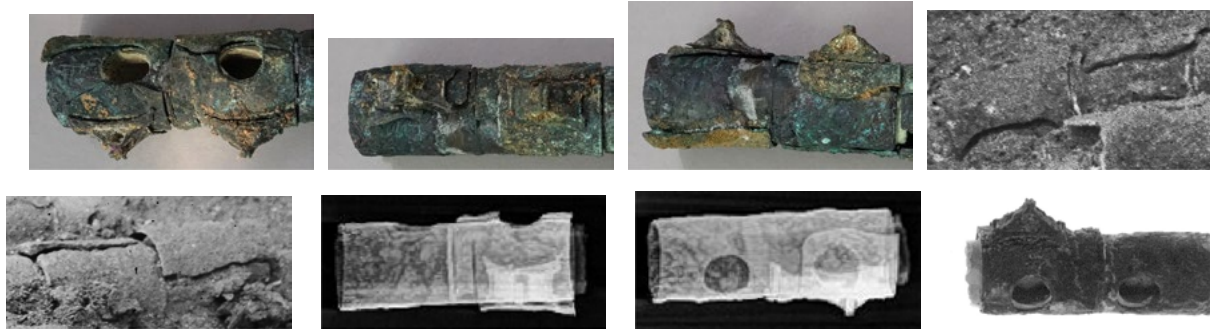
068 Tray: 10-15 Bodley: 3-13 S2-H-10

Lng=75, Di=7.4, Do=14.25, H1Pos=11.5, H1Dl=6.3, H1Dt=5.3, H1Az=0, H1BAz=-115, H1BPos=-1.5, H1BS=T, H2Pos=28, H2Dl=4.9, H2Dt=4.2, H2Az=0, H2BAz=-115, H2BPos=2, H2BS=T, H3Pos=45.2, H3Dl=6.3, H3Dt=4.5, H3Az=0, H3BAz=-115, H3BPos=2, H3BS=T, H4Pos=65, H4Dl=6.4, H4Dt=5.9, H4Az=0, H4BAz=-115, H4BPos=2.5, H4BS=T, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.9, Cu=97.4, Sn=1.6, Pb=0.1, Sct1=56.2, Sct2=37.8, Sct3=21, Cuts=3



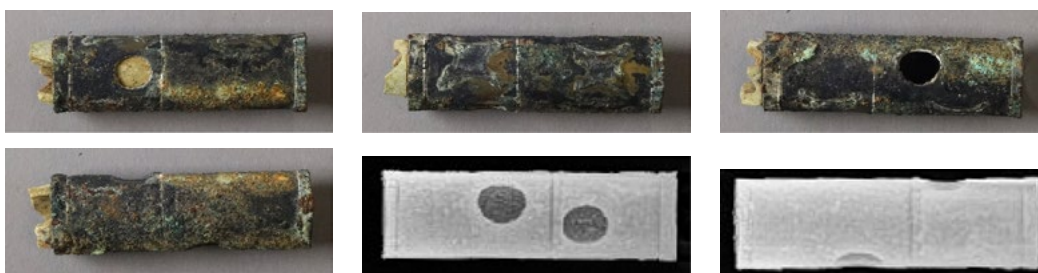
069 Tray: 10-14 Bodley: 3-11 Joined to: 103 S1-H-07

Lng=40.7, Di=7.8, Do=14.25, H1Pos=8, H1Dl=6.8, H1Dt=6.8, H1Az=0, H1BAz=-112, H1BPos=1, H1BS=T, H2Pos=27.1, H2Dl=7, H2Dt=6.5, H2Az=0, H2BAz=-112, H2BPos=5, H2BS=T, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.0, Cu=93.9, Sn=6.0, Pb=0.0, Sct1=20, Cuts=1



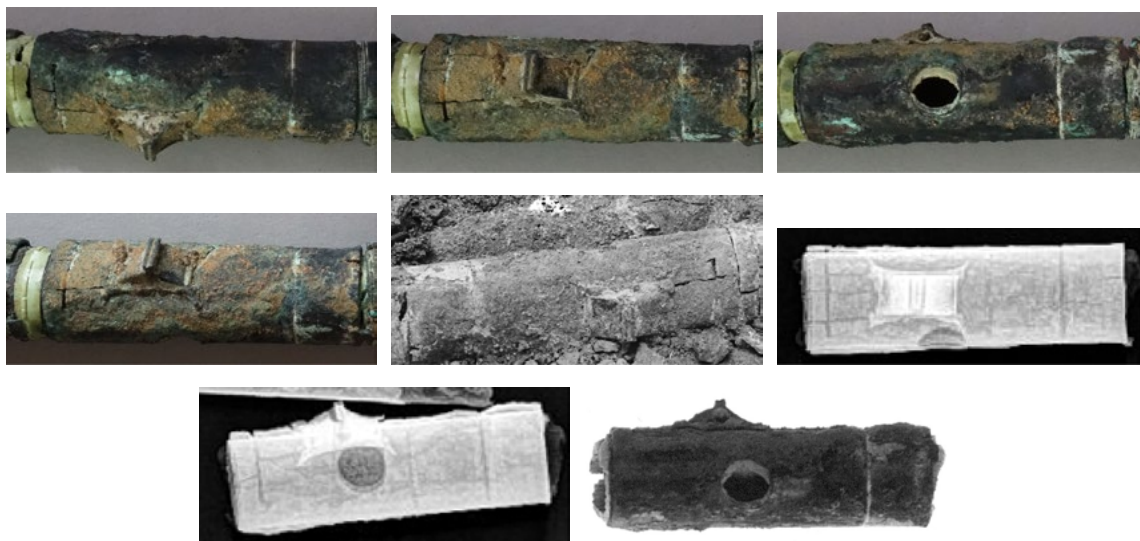
070 Tray: 10-13 S1-H-09

Lng=46.8, Di=7.5, Do=14.25, H1Pos=18.6, H1Dl=7.2, H1Dt=6.3, H1Az=-168, H1BAz=-105, H1BPos=-7, H1BS=K, H2Pos=32.1, H2Dl=6.5, H2Dt=5.8, H2Az=0, H2BAz=87, H2BPos=3, H2BS=K, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.05, Cu=90, Sn=9.35, Pb=0.1, Fe1=0.1, Cu1=89.9, Sn1=9.9, Pb1=0.1, Fe2=0.0, Cu2=91.1, Sn2=8.8, Pb2=0.1, Sct1=2.4, Sct2=43.8, Sct3=26.5



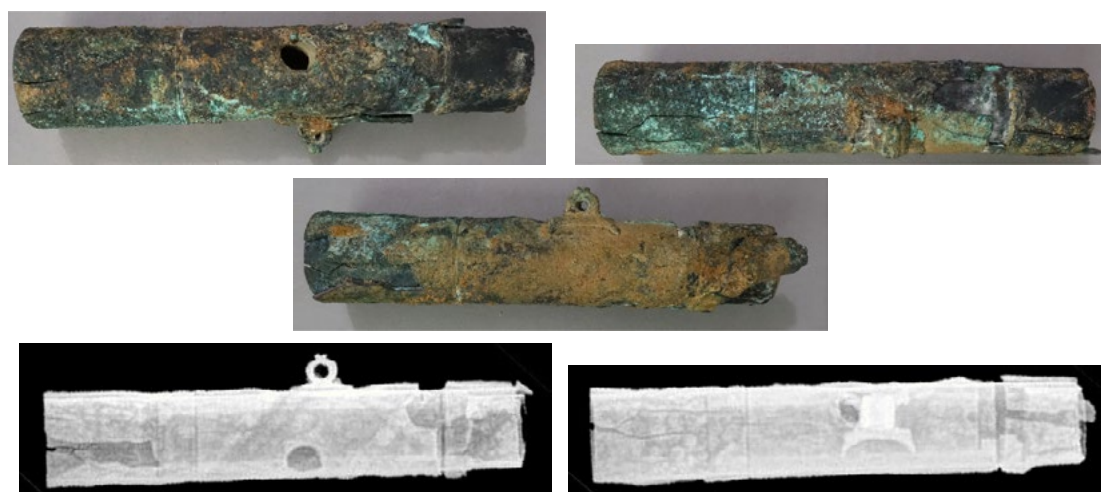
071 Tray: 10-12 Bodley: 3-03 Joined to: 095 LL-03

Measurements see compound 001, Lng=53, Cuts=1



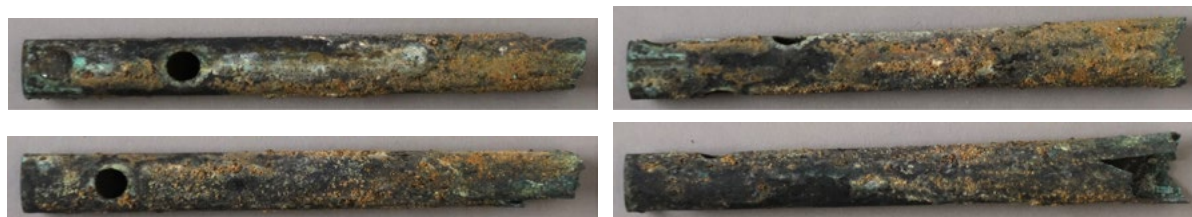
072 Tray: 10-11 LL-07

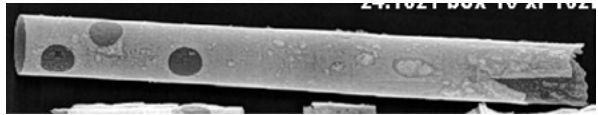
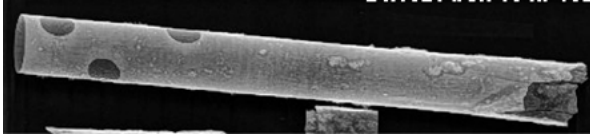
Lng=84.8, Di=8.5, Do=16, H1Pos=38.75, H1Dl=5.5, H1Dt=5.5, H1Az=0, H1BAz=-137, H1BPos=-4, H1BS=R, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.2, Cu=94.0, Sn=5.7, Pb=0.1, Sct1=14, Sct2=57.8, Sct3=64.1, Cuts=1



073 Tray: 10-10 Bodley: NP-2 W2-L-04

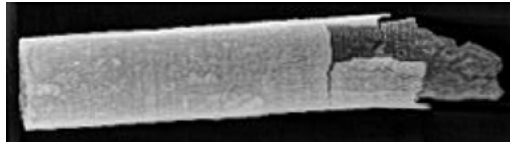
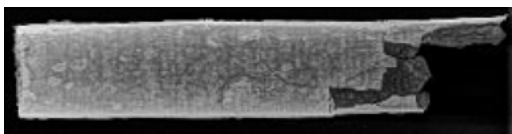
Lng=136.5, Do=14.5, H1Pos=8, H1Dl=8.2, H1Dt=7.2, H1Az=-10, H2Pos=22, H2Dl=7.65, H2Dt=7.3, H2Az=154, H3Pos=39, H3Dl=8, H3Dt=7.1, H3Az=0, E1P=1, E1T=Sm, E2P=0, Fe=0.0795, Cu=90.8195, Sn=9.151, Fe1=0.1, Cu1=91.0, Sn1=9.0, Fe2=0.059, Cu2=90.639, Sn2=9.302





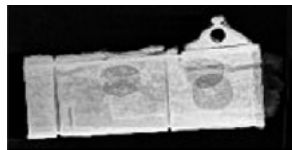
074 Tray: 10-09 W1-L-07

Lng=73, Do=14.25, E1P=0, E1T=B, E2P=1, E2T=Sm, Fe=0.1, Cu=98.0, Sn=1.9, Pb=0.0



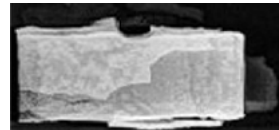
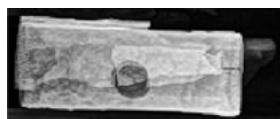
075 Tray: 10-08 S2-H-08

Lng=41, Di=6.5, Do=14.25, H1Pos=17.5, H1DI=6.8, H1Dt=6.5, H1Az=0, H1BAz=120, H1BPos=-3, H1BS=T, H2Pos=32.5, H2DI=6.8, H2Dt=6.8, H2Az=4, H2BAz=120, H2BPos=2.5, H2BS=T, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.7, Cu=98.3, Sn=0.9, Pb=0.1, Sct1=24.9, Sct2=5.5, Cuts=2



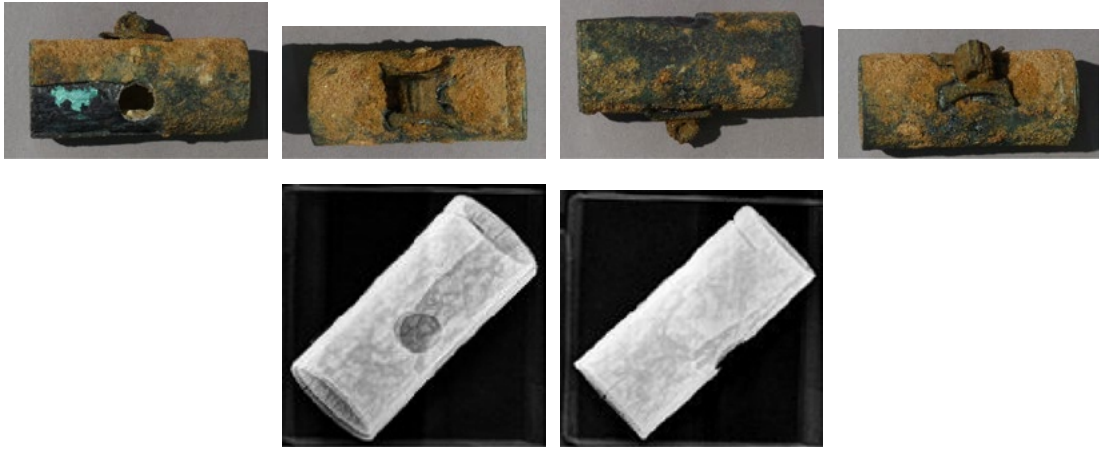
076 Tray: 10-07 LR-09

Lng=40, Di=9, Do=16, H1Pos=19.9, H1DI=5.7, H1Dt=6.4, H1Az=0, H1BAz=120, H1BPos=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.2, Cu=98.0, Sn=1.8, Pb=0.1, Cuts=1



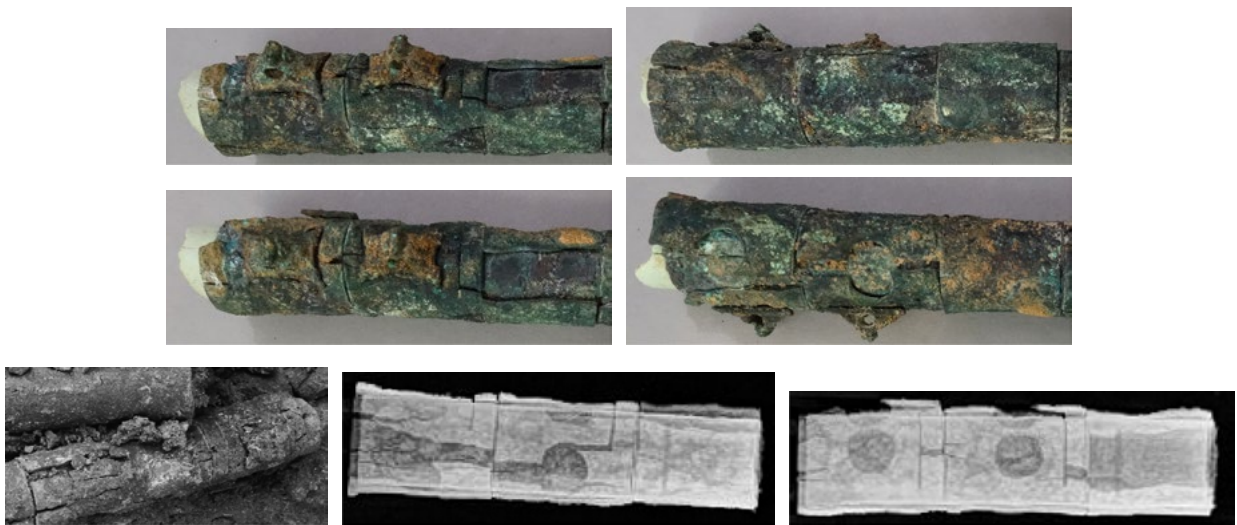
077 Tray: 10-06 LR-08

Lng=37.5, Di=8.9, Do=16, H1Pos=18, H1Dl=6.35, H1Dt=6.25, H1Az=0, H1BAz=-146, H1BPos=0, H1BS=R, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.0, Cu=94.1, Sn=5.8, Pb=0.1, Di=8.6, Cuts=1



078 Tray: 10-05 S1-H-04

Lng=63.6, Di=7.9, Do=14.25, H1Pos=30, H1Dl=6.7, H1Dt=6.5, H1Az=0, H1BAz=-101, H1BPos=1, H1BS=T, H2Pos=52.5, H2Dl=6.9, H2Dt=6.5, H2Az=0, H2BAz=-103, H2BPos=2, H2BS=T, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.7, Cu=93.7, Sn=5.6, Sct1=41, Sct2=19.5, Cuts=2



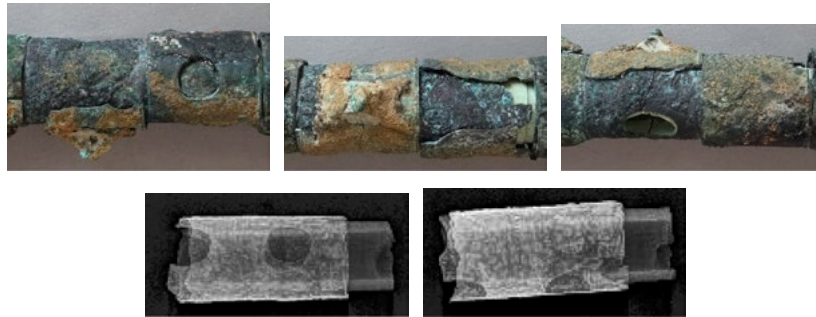
079 Tray: 10-04 Bodley: 4-05 Joined to: 080 S2-L-05

Measurements see compound 067, Lng=45, Di=7.6, Fe=0.1, Cu=96.75, Sn=3.15, Pb=0.05, Fe1=0.1, Cu1=95.8, Sn1=4.1, Pb1=0.0, Fe2=0.1, Cu2=97.7, Sn2=2.2, Pb2=0.1, Cuts=2



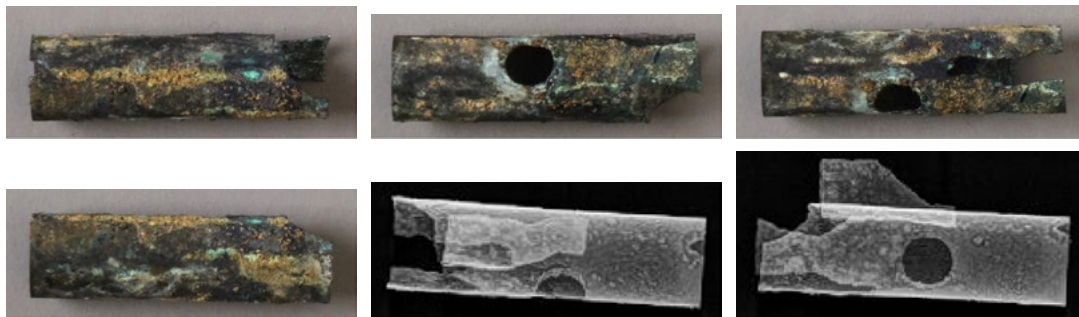
080 Tray: 10-03 Joined to: 067 S2-L-05

Measurements see compound 067, Lng=37.5, Fe=0.05, Cu=91.4, Sn=8.5, Pb=0.05, Fe1=0.1, Cu1=90.0, Sn1=9.9, Pb1=0.0, Fe2=0.0, Cu2=92.8, Sn2=7.1, Pb2=0.1, Cuts=1



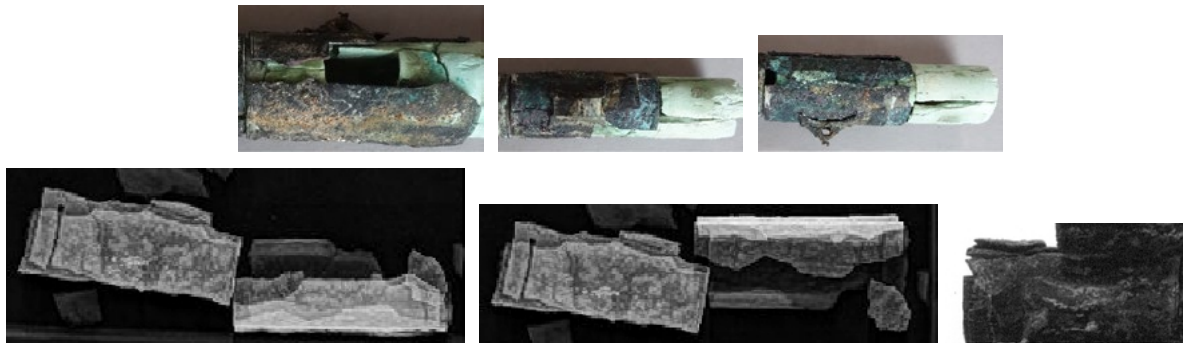
081 Tray: 11-01 W2-H-02

Lng=50, Do=14.5, H1Pos=27.5, H1DI=8, H1Dt=7, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=92.0, Sn=8.0



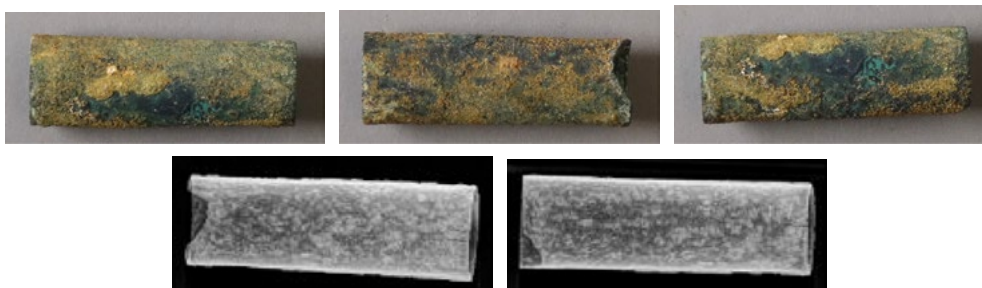
082 Tray: 11-02 Bodley: 6-03b5 Joined to: 086 HR-08

Measurements see compound 086, Lng=35, Di=8.9, Cuts=1



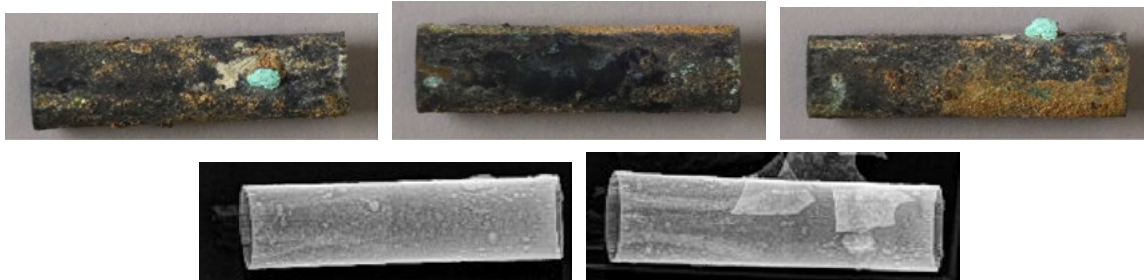
083 Tray: 11-03 S2-H-11

Lng=45.7, Do=14.25, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=98.6, Sn=1.2, Pb=0.1



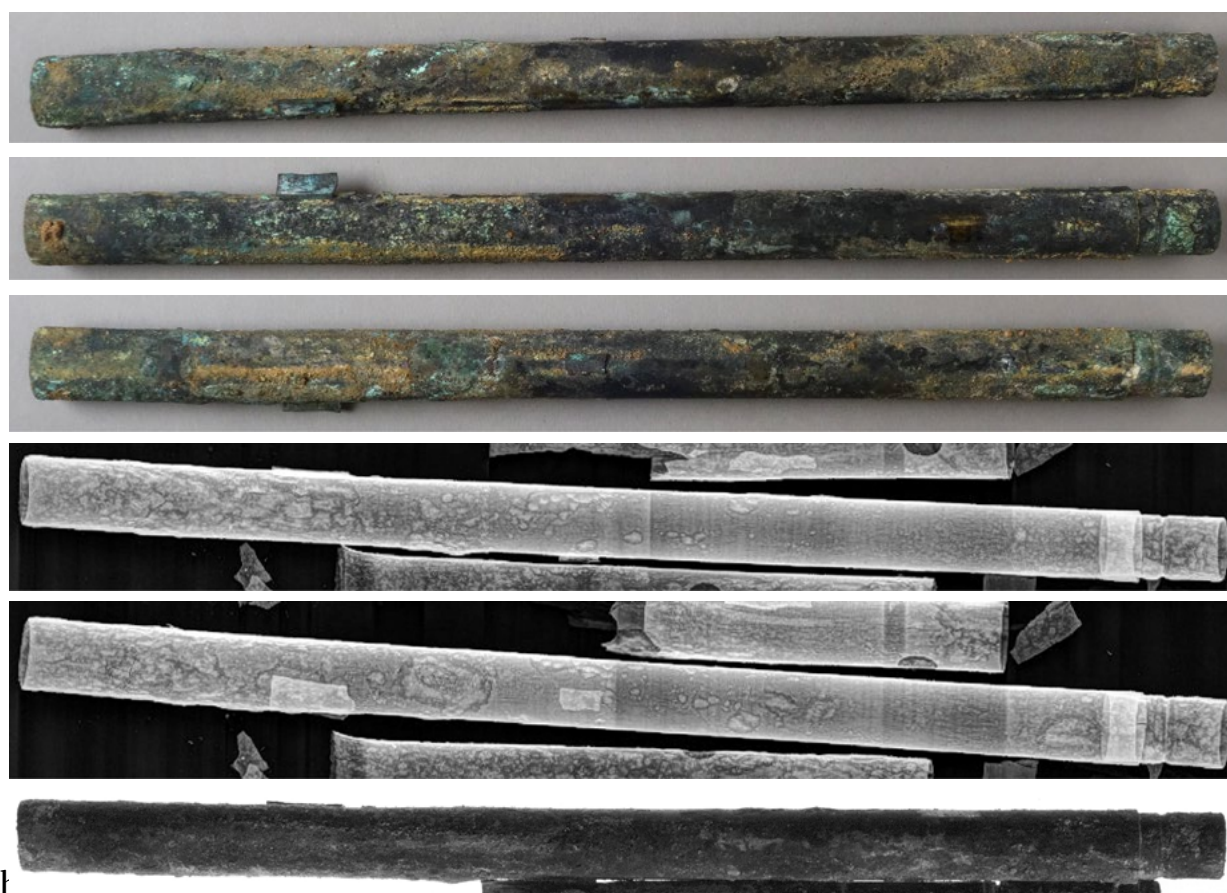
084 Tray: 11-04 W1-H-02

Lng=53.3, Do=14.5, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=90.0, Sn=9.9



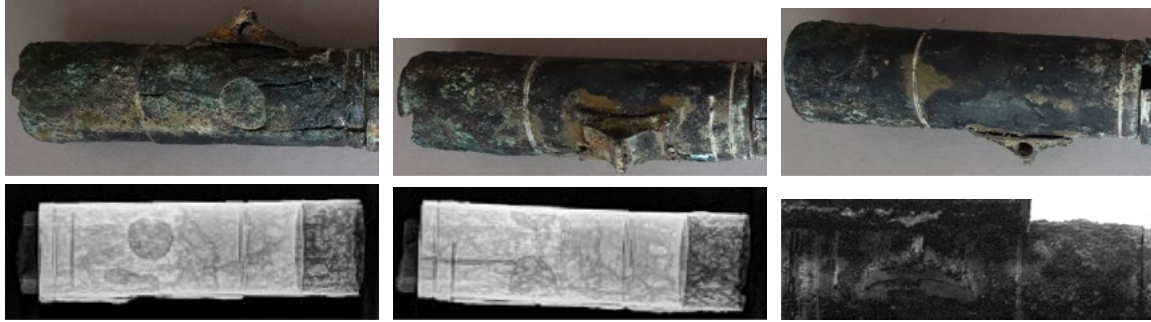
085 Tray: 11-05 Bodley: 6-03c LL-06

Lng=267, Do=16, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=90.0, Sn=9.8, Pb=0.1, Sct1=19.5, Sct2=13.5



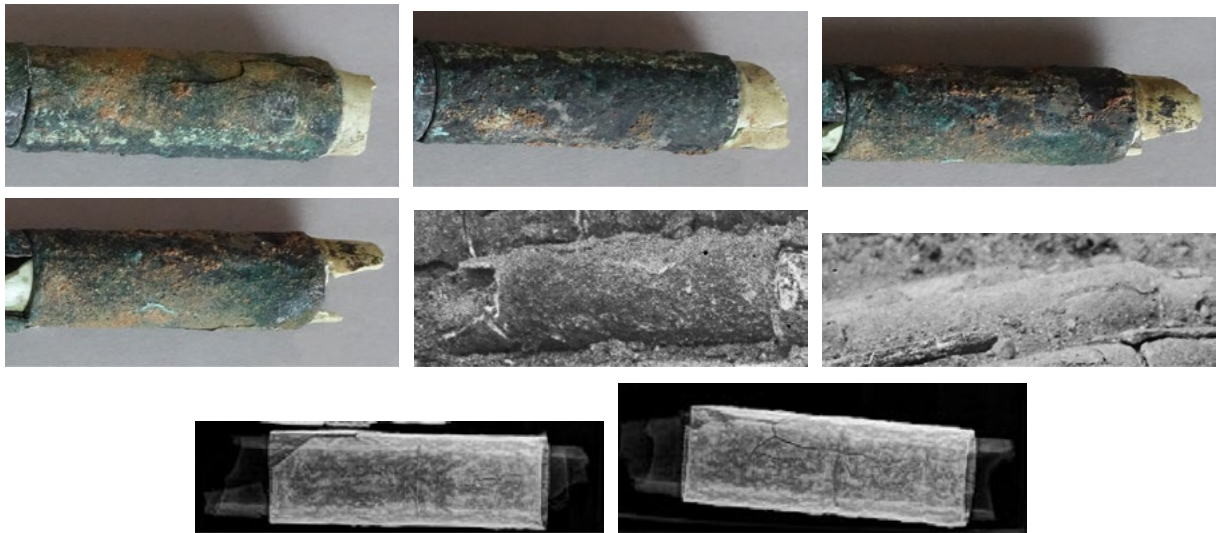
086 Tray: 11-06 Bodley: 6-03b2-4 Joined to: 082 HR-08

Measurements see compound 086, Lng=53.3, Di=9.2, Fe=0.2, Cu=90.1, Sn=9.6, Pb=0.1, Cuts=1



087 Tray: 11-07 HL-03

Measurements see compound 041, Lng=48.3, Sp2L=10, Sp2D≈14, Di=9.4



088 Tray: 11-08 Bodley: 6-02c

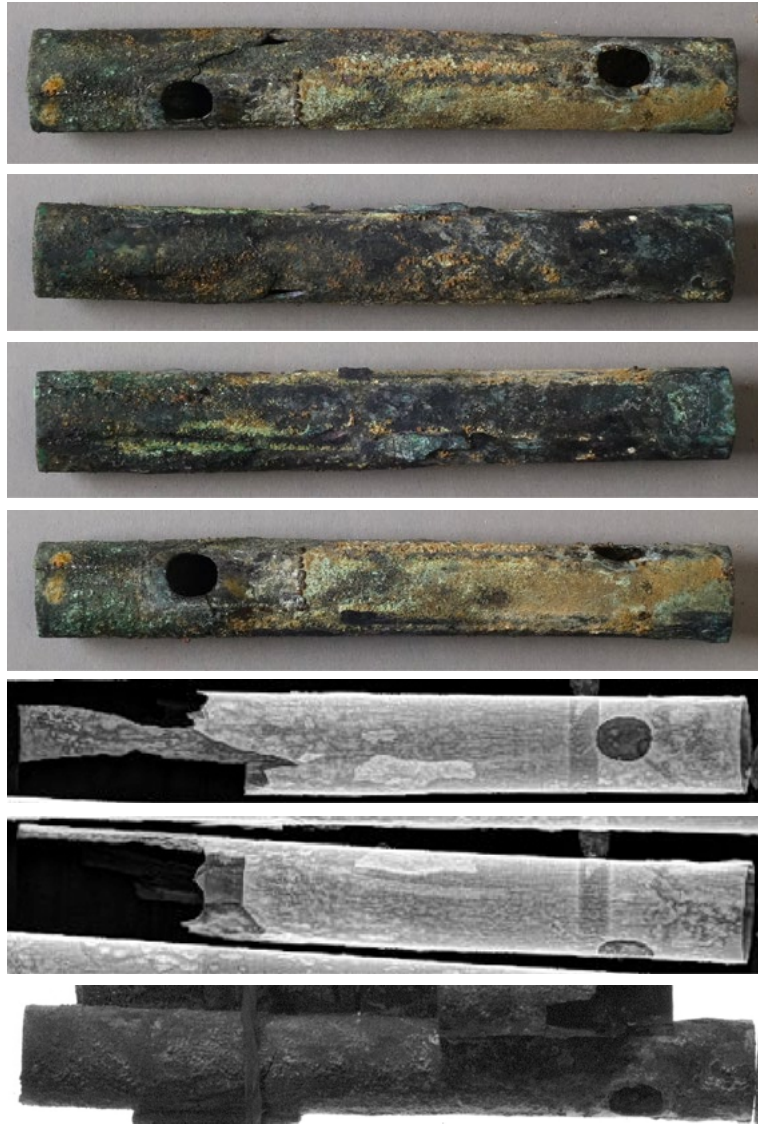
S2-L-04

Lng=44, Di=7.7, Do=14.25, H1Pos=10.8, H1DI=6.9, H1Dt=6.9, H1Az=0, H1BAz=120, H1BPos=2, H1BS=T, H2Pos=33.7, H2DI=7, H2Dt=7.1, H2Az=0, H2BAz=120, H2BPos=-2, H2BS=T, E1P=1, E1T=Sp, Sp1L≈13, Sp1D≈12, E2P=1, E2T=Sm, Fe=0.1, Cu=96.6, Sn=3.3, Pb=0.0, Sct1=21.7, Cuts=2



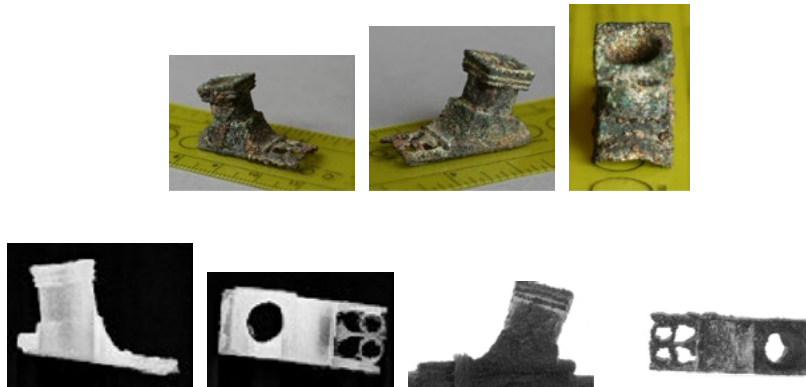
089 Tray: 11-09 Bodley: 6-02c HL-10

Lng=116, Do=16, H1Pos=18.5, H1Dl=8.7, H1Dt=7.1, H1Az=50, H2Pos=90.9, H2Dl=6, H2Dt=6, H2Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=94.0, Sn=5.8, Pb=0.1, Pt1=65.7,-48, Pt2=71.8,-48



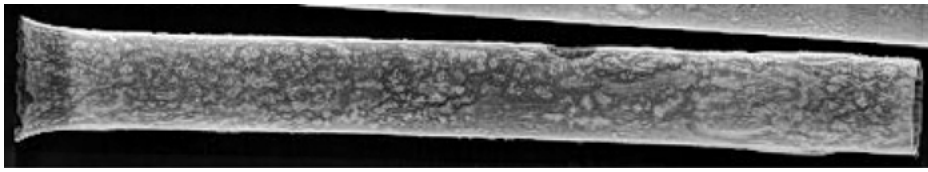
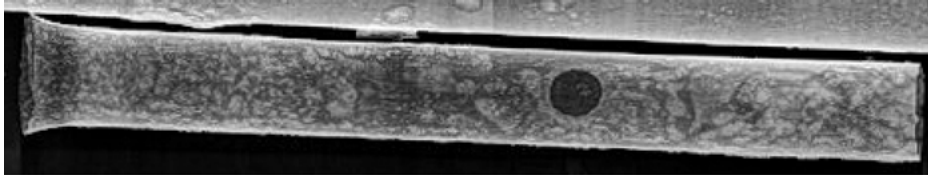
090 Tray: 11-10 Bodley: 6-03b1 Joined to: 089

Lng=26.5



091 Tray: 11-11 Bodley: 4-17 W1-H-01

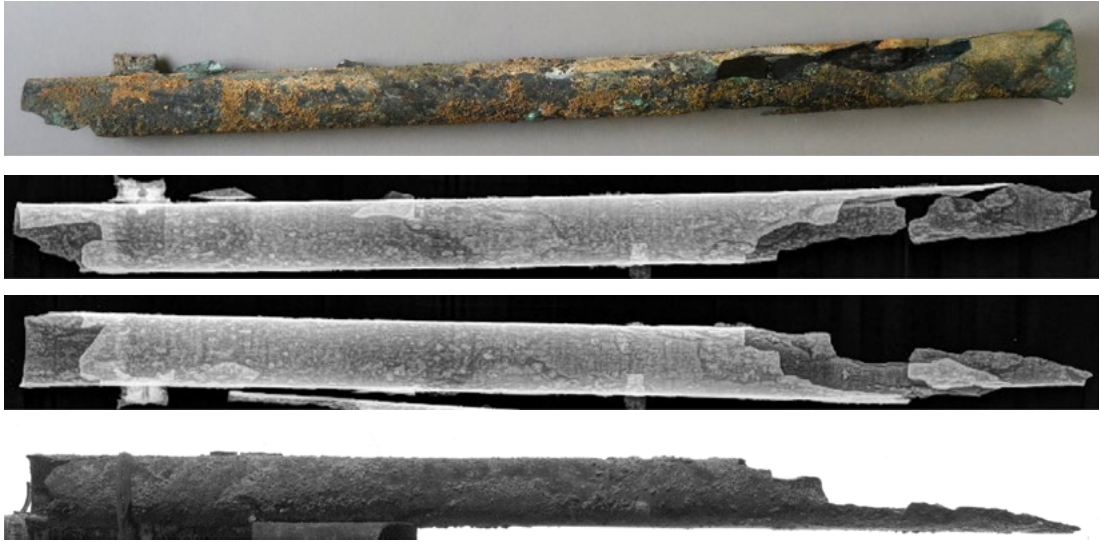
Lng=133, Do=14.5, H1Pos=82, H1Dl=7.4, H1Dt=7.25, H1Az=0, E1P=1, E1T=B, E2P=1, E2T=Sm, Fe=0.1, Cu=98.3, Sn=1.7



092 Tray: 11-12 Bodley: 6-02a HR-01

Lng=274, Do=16, E1P=1, E1T=B, E2P=1, E2T=Sm, Fe=0.1, Cu=94.0, Sn=5.8, Pb=0.1





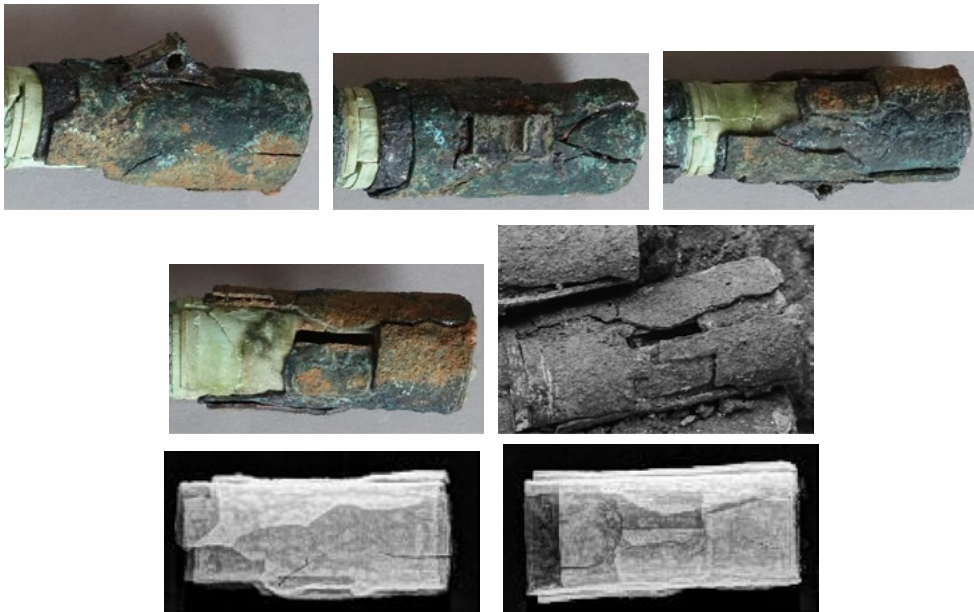
093 Tray: 11-13

Lng≈37.5



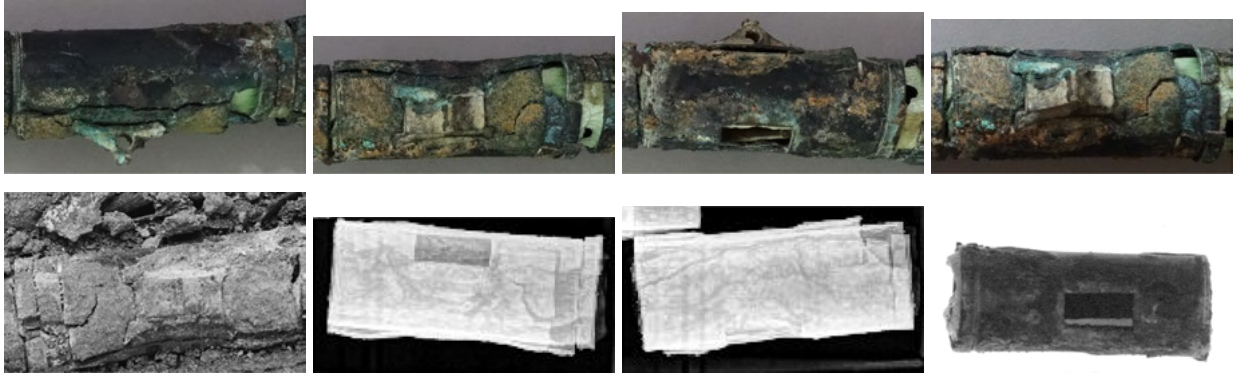
094 Tray: 12-01 HL-07

Lng=37, Di=9.5, Do=16, H1Pos=17.75, H1Dl=10.5, H1Dt≈4.5, H1S=R, H1Az=0, H1BAz=163, H1BPos=0, H1BS=T, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Sp2L=8, Sp2D≈14, Cuts=1



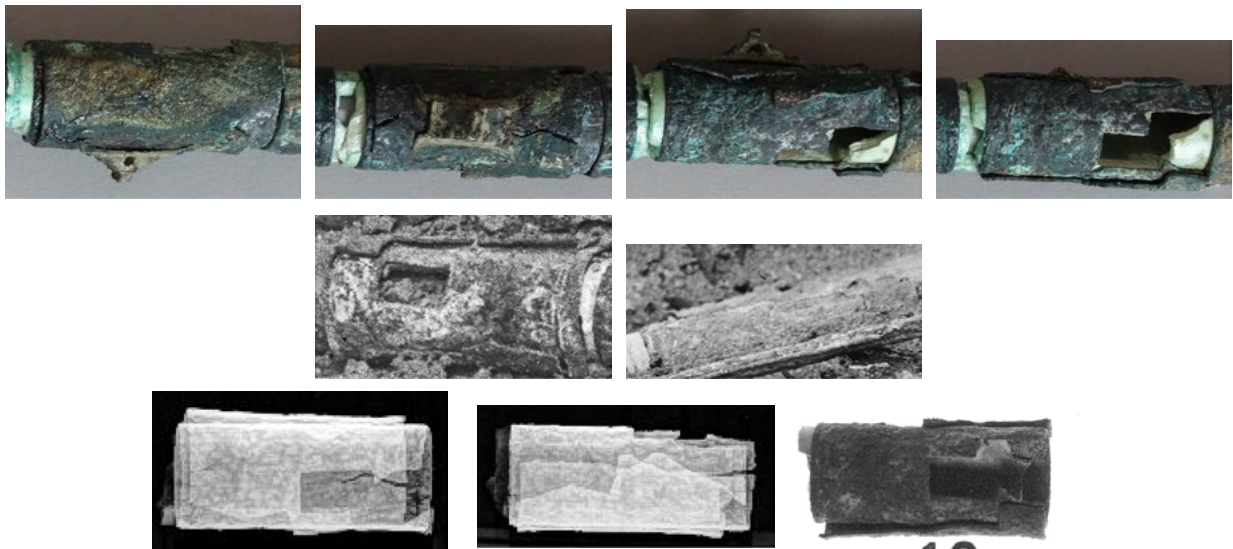
095 Tray: 12-02 Bodley: 4-11 Joined to: 001 LL-03

Measurements see compound 001, Lng=43, Di=9.6, Fe=0.0, Cu=93.3, Sn=6.1, Pb=0.6, Cuts=1



096 Tray: 02-07 Bodley: 4-12 Joined to: 087 HL-03

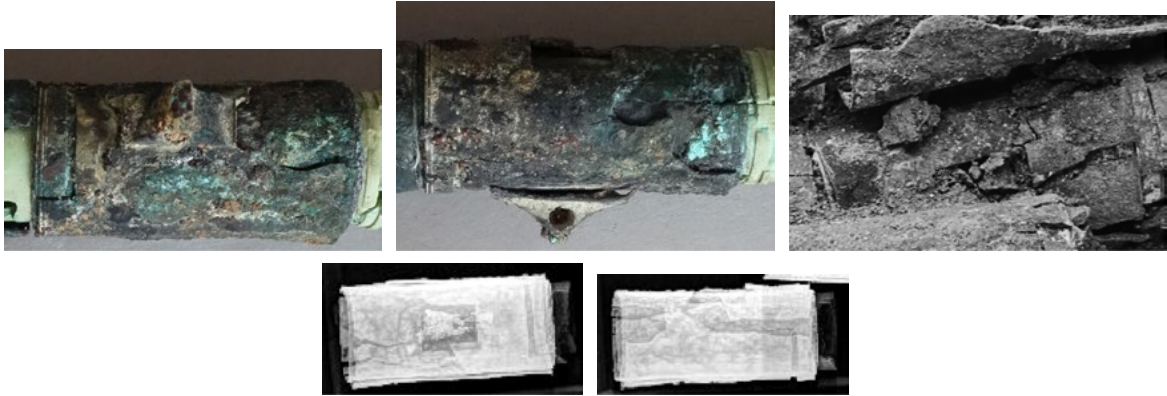
Measurements see compound 041, Lng=42.2, Di=9.9, Cuts=1



097 Tray: 12-04 Bodley: Joined to: 094 HL-07

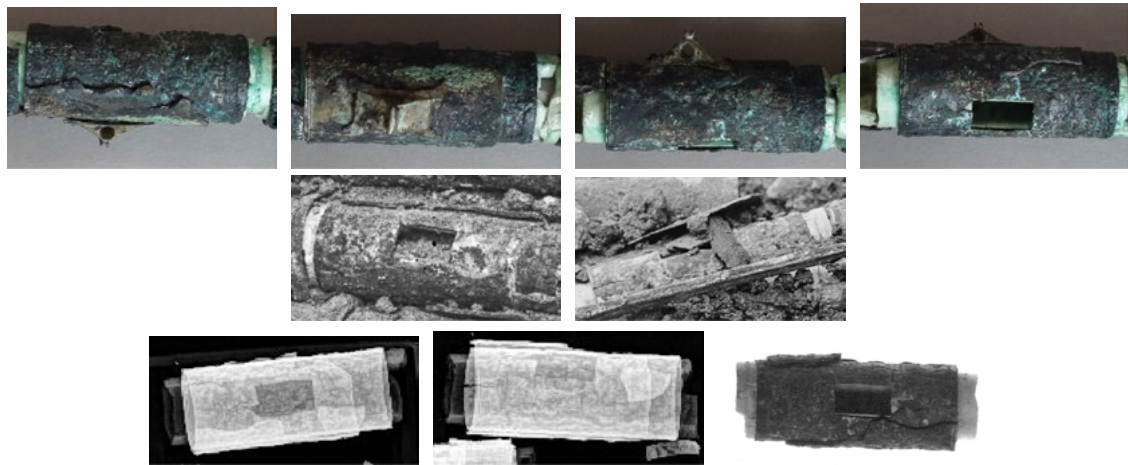
Lng=34, Di=9.7, Do=16, H1Pos=15.75, H1Dl=9, H1Dt=5.4, H1S=R, H1Az=0, H1BAz=-162, H1BPos=-1, H1BS=T, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Di=9.8, Sp2L=20, Sp2D≈14, Cuts=1





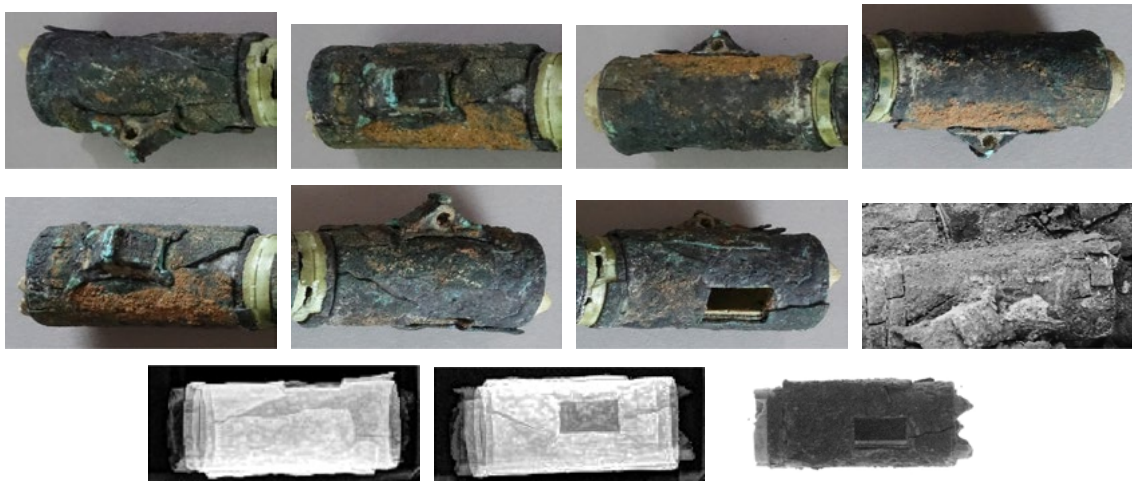
098 Tray: 12-05 Bodley: 4-14 Joined to: 096 HL-03

Measurements see compound 041, Lng=38.5, Di=9.8, Cuts≈1



099 Tray: 12-06 Bodley: 4-13 Joined to: 071 LL-03

Measurements see compound 001, Lng=38.7, Di=9.8, Cuts=1



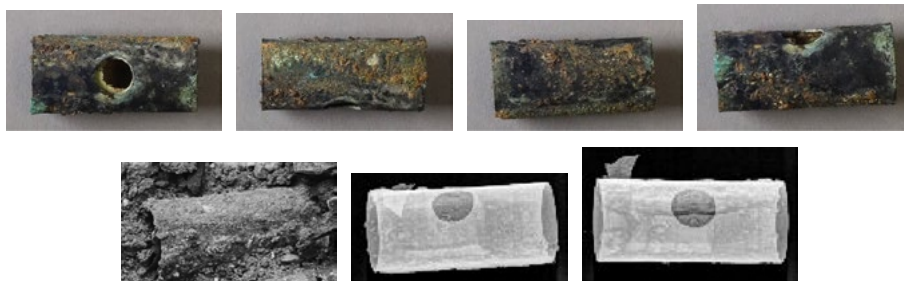
100 Tray: 12-07 Bodley: 6-03b1 HR-09

Lng=61.8, Do=16, H1Pos=36, H1Dl=6.3, H1Dt=6.5, H1Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.2, Cu=90.8, Sn=9.0, Pb=0.1, Pt1=14.07,-30



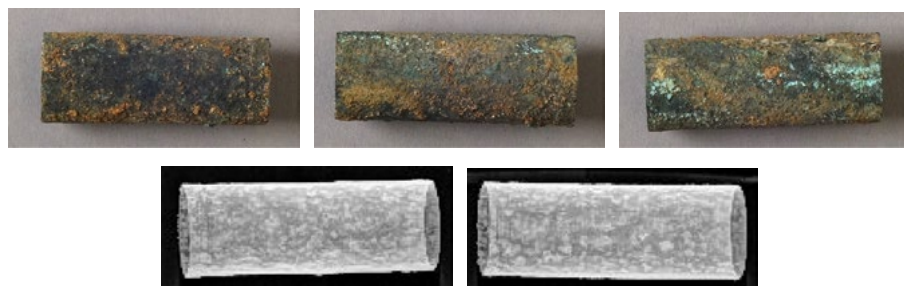
101 Tray: 12-08 S2-H-03

Lng=30.8, Di \approx 7.5, Do=14.25, H1Pos=15.5, H1Dl=7.4, H1Dt=6.6, H1Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.2, Cu=90.6, Sn=9.0, Pb=0.2



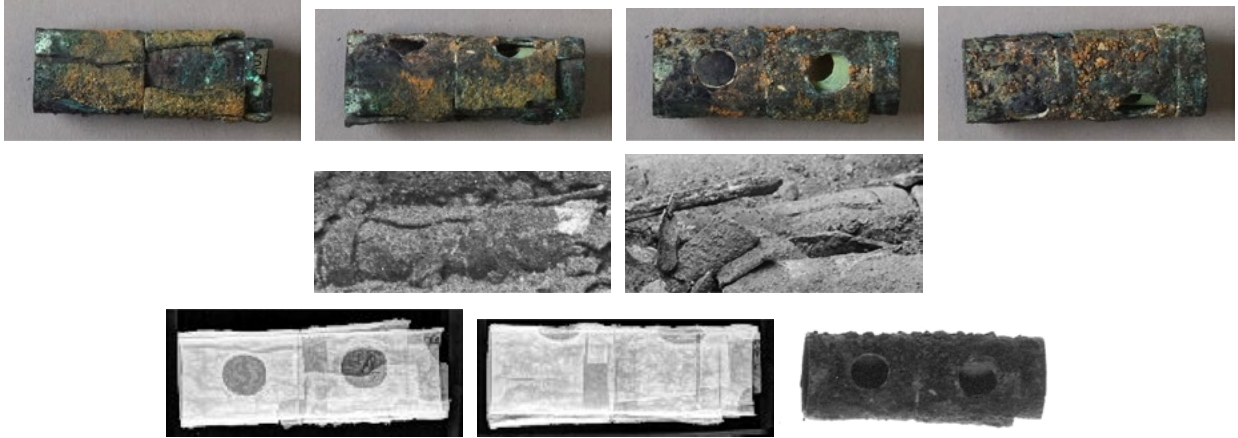
102 Tray: 12-09 HR-12

Lng=41.5, Do=16, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.2, Cu=99.1, Sn=0.7, Pb=0.0



103 Tray: 12-10 Bodley: 4-06 Joined to: 069 S1-H-07

Lng=42.4, Di=10.3-10.6, Do=14.25, H1Pos=10.4, H1DI=6.3, H1Dt=5.8, H1Az=0, H1BAz=-105, H1BPos=-3, H2Pos=30, H2DI=6.4, H2Dt=6.5, H2Az=0, H2BAz=-93, H2BPos=-4, H2BS=T, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.15, Cu=94.8, Sn=5.0, Pb=0.1, Fe1=0.2, Cu1=93.0, Sn1=6.7, Pb1=0.2, Fe2=0.1, Cu2=96.6, Sn2=3.3, Pb2=0.0, Sct1=37, Sct2=19.5, Sn3=6.7, Pb4=0.2, Cuts=2



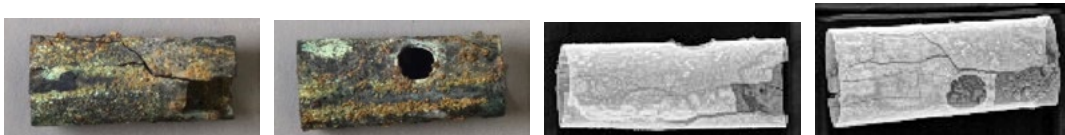
104 Tray: 12-11 S2-H-09

Lng=24.5, Di≈7.5, Do=14.6, H1Pos=13, H1DI=6, H1Dt=5.1, H1Az=0, H1BAz=115, H1BPos=-1.5, H1BS=K, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=88.2, Sn=11.7, Pb=0.0



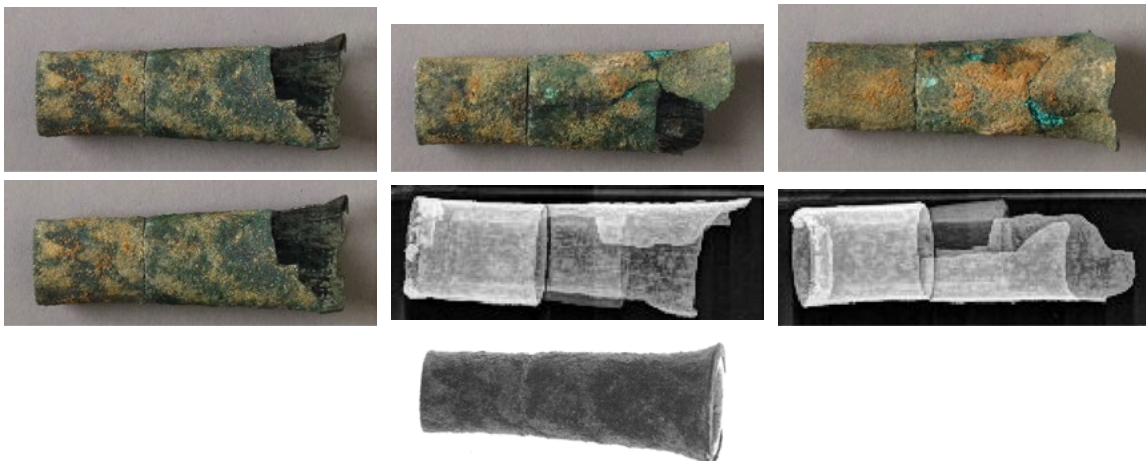
105 Tray: 12-12 W1-L-06

Lng=36.5, Do=15, H1Pos=15.2, H1Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=89.9, Sn=9.9



106 Tray: 12-13 Bodley: 4-16 HL-14

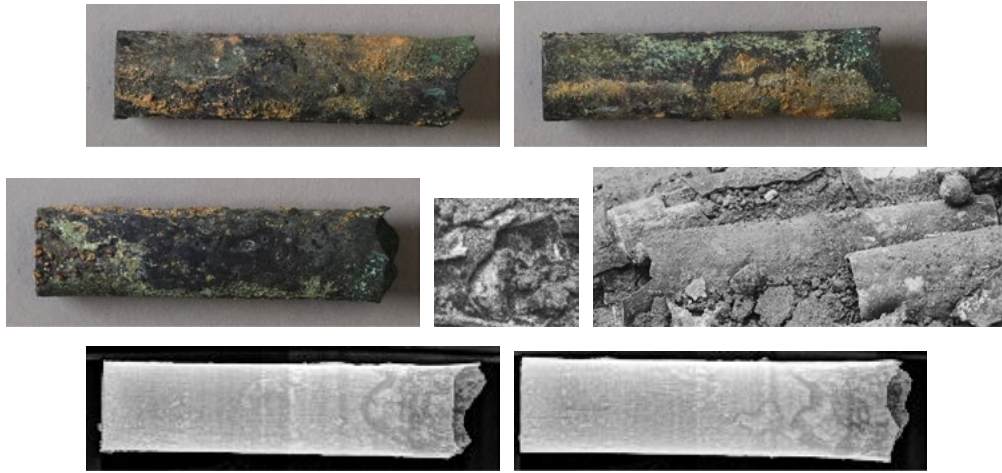
Lng=53.2, Do=16, E1P=1, E2P=1, E2T=R, Fe=0.2, Cu=97.0, Sn=2.7, Pb=0.1



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107 Tray: 12-14 W1-L-01

Lng=59, Do=14.25, E1P=0, E1T=B, E2P=1, E2T=Sm, Fe=0.2, Cu=91.0, Sn=8.8



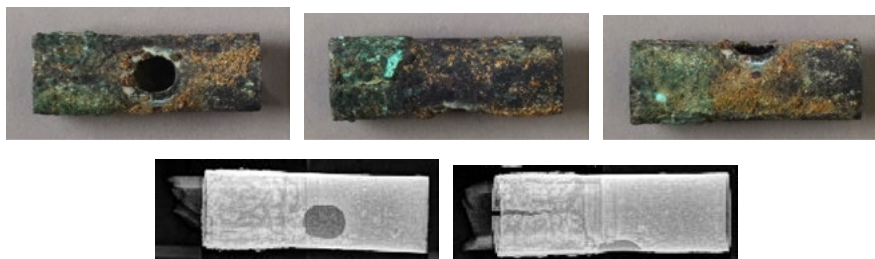
108 Tray: 12-15 LR-13

Lng=52.5, Di \approx 9.3, Do=16, E1P=1, E2P=1, E2T=R



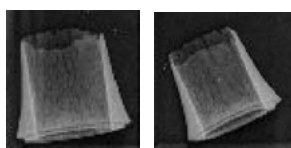
109 Tray: 12-16 W1-L-04

Lng=40.5, Do=14.5, H1Pos=21.7, H1Dl=7.7, H1Dt=6.6, H1Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.0, Cu=98.0, Sn=1.9, Pb=0.0



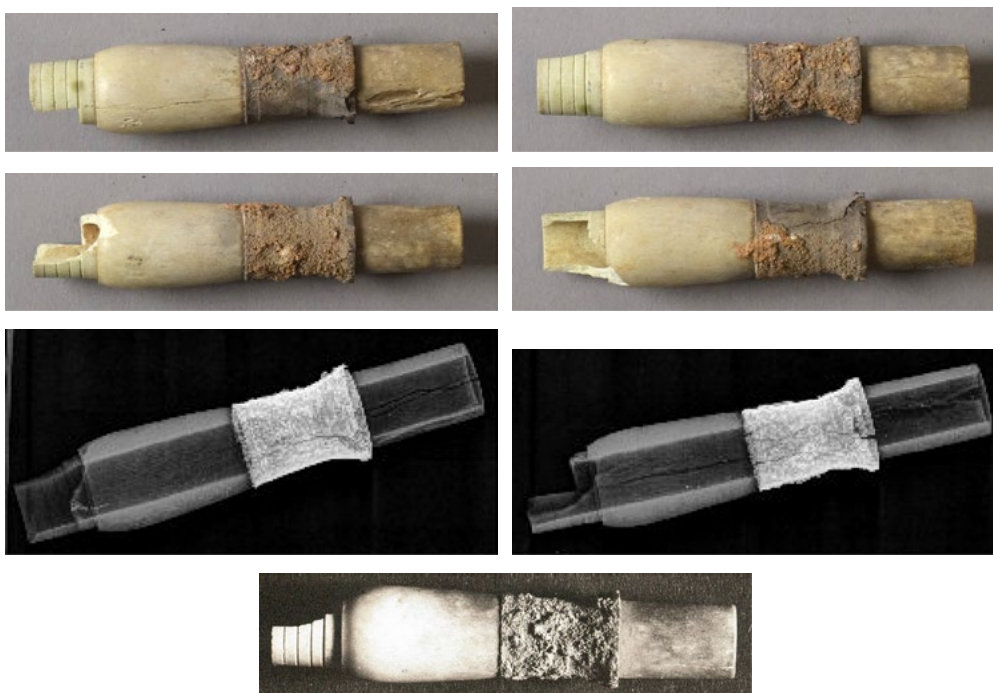
110 Tray: 12-17

Lng=14.7, Di≈7.2, Do=14.2-15.6, E1P=0, E2P=1, E2T=R



111 Tray: 12-18 Bodley: 8-01 S1-L-11

Lng=41.6, Di=7.4, E1P=1, E2P=1, Sp1L=18.5, Sp1D=11.4, Sp2L=10.3, Sp2D=10.9



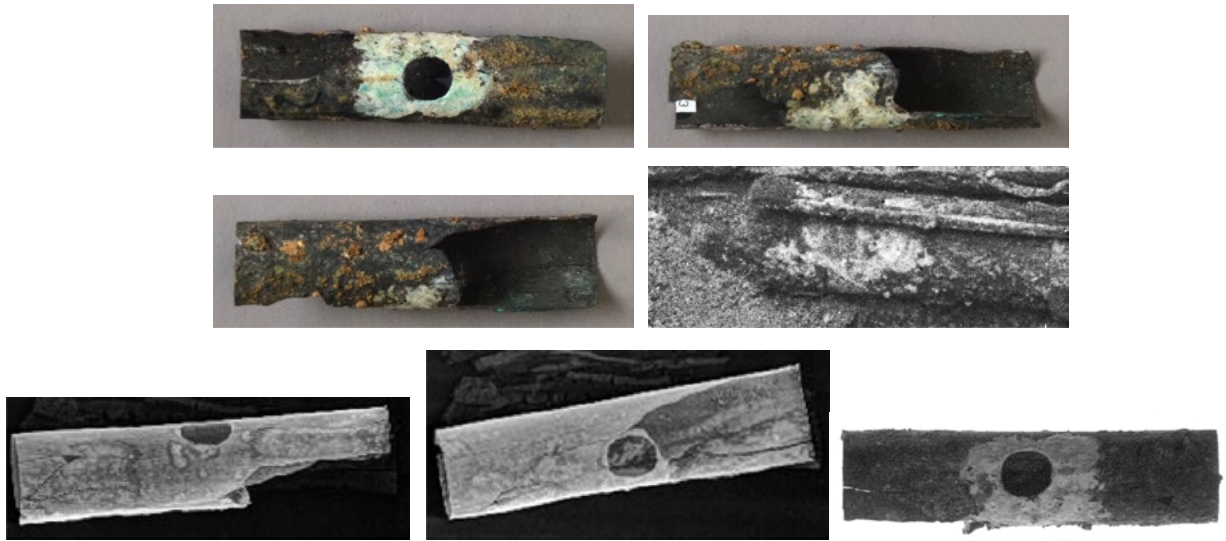
112 Tray: 10-16 Bodley: 3-01? HR-14

Lng=27.5, Di=9.2, Do=15, E1P=1, E2P=0



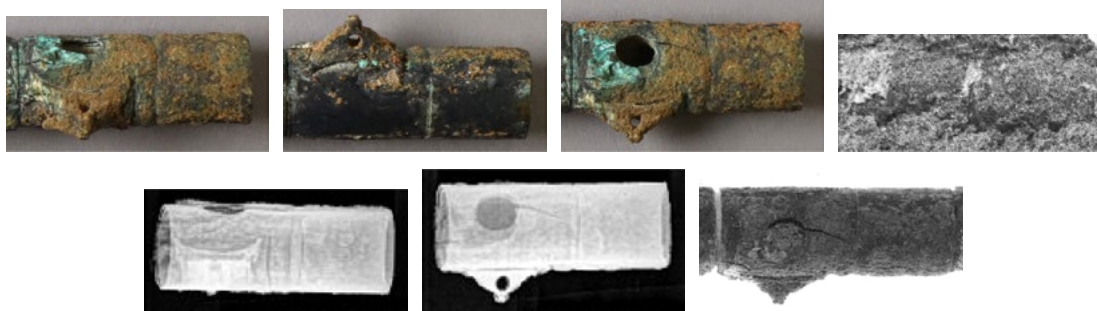
113 Tray: 10-17 Bodley: 4-03 W2-L-02

Lng=60, Do=14.5, H1Pos=31, H1Dl=7.9, H1Dt=7, H1Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=97.5, Sn=2.4



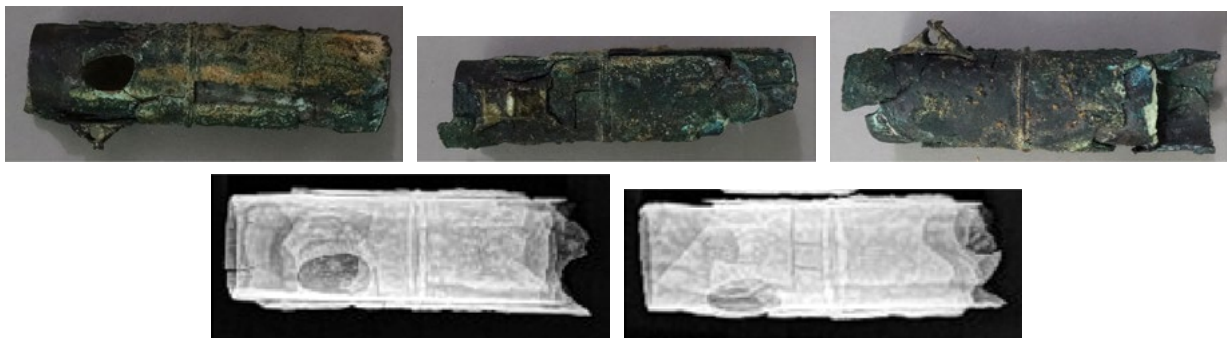
114 Tray: 10-18 Bodley: 3-12 Joined to: 004 S2-H-06

Measurements see compound 004, Lng=37.5, Di=7.4, Fe=0.1, Cu=13.0, Sn=31.9, Pb=55.0, Cuts=1



115 Tray: 10-19 S1-L-06

Lng=56.8, Di=7.9, Do=14.25, H1Pos=9.2, H1Dl=7.5, H1Dt=6.3, H1Az=-5, H1BAz=-133, H1BPos=7.5, H1BS=T, H2Pos=42, H2Dl=7.3, H2Dt=5.5, H2Az=0, H2BAz=-133, H2BPos=2.5, H2BS=T, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=95.5, Sn=4.4, Pb=0.0, Sct1=29, Cuts=1



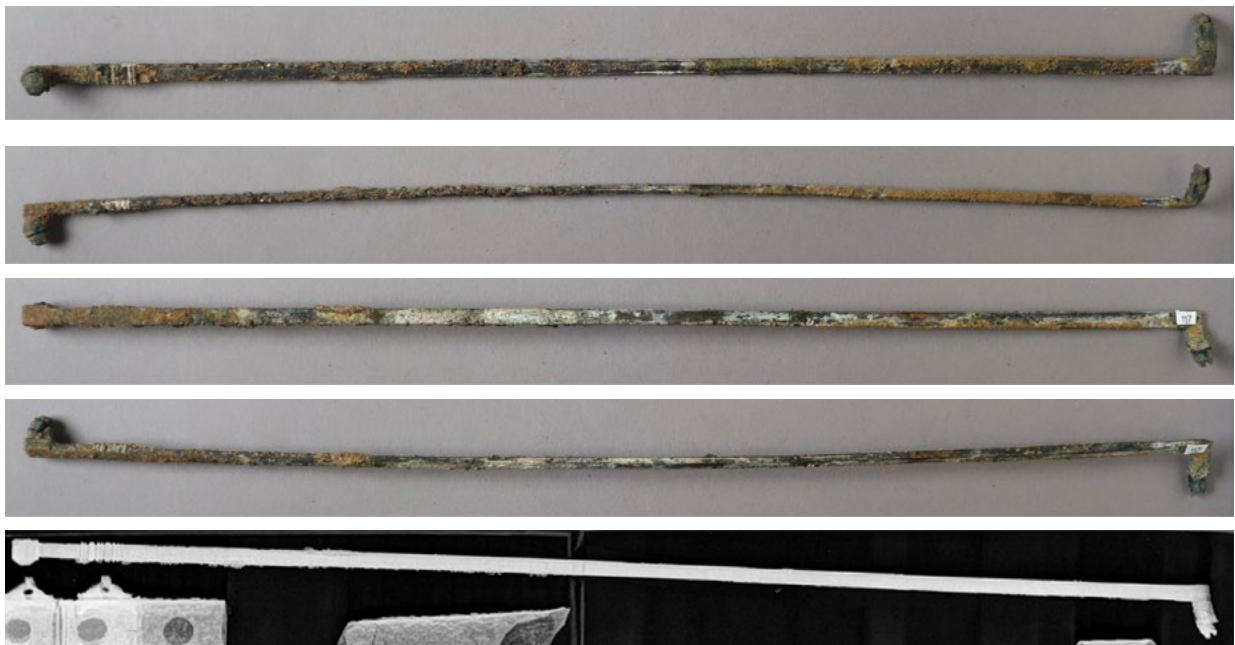
116 Tray: 10-20 S2-H-01

Lng=65, Do=14.5, E1P=1, E1T=B, E2P=1, E2T=Sm, Fe=0.2, Cu=95.2, Sn=4.6



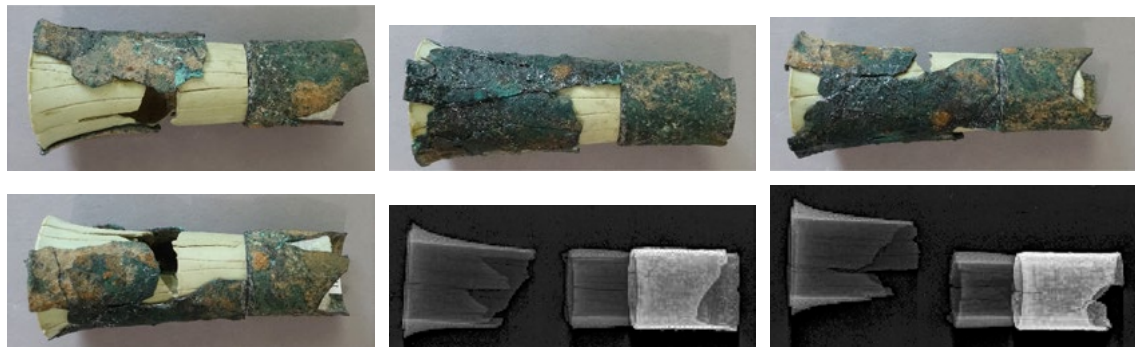
117 Tray: 10-21 Joined to: 032

Lng=277



118 Tray: 10-22 LL-11

Lng=52.4, Di=9.4, Do=16.5, E1P=1, E2P=1, E2T=R, Sct1=18.5



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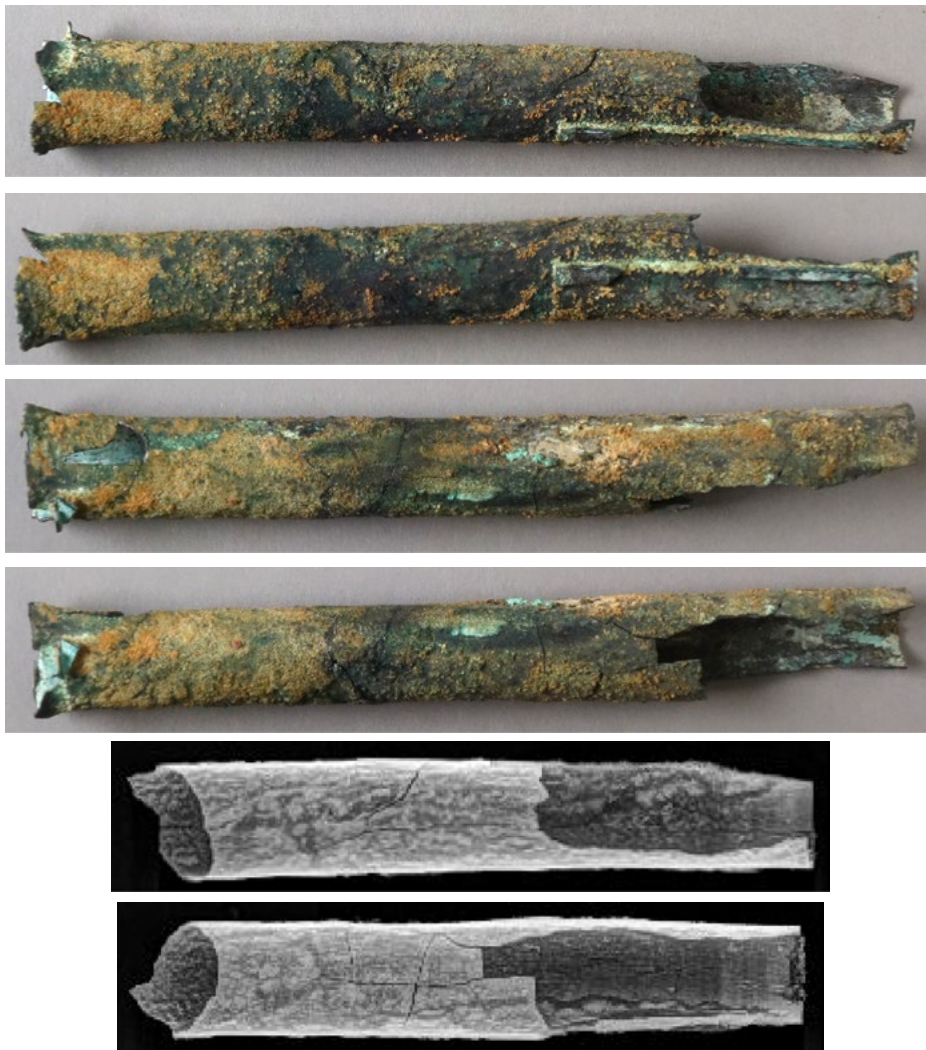
119 Tray: 10-23 S1-L-09

Lng=20, Do=14.25, H1Pos=5.5, H1Dl=6.4, H1Dt=6.2, H1Az=0, H1BAz=115, H1BPos=3.5, H1BS=T, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=91.1, Sn=8.8, Cuts=1



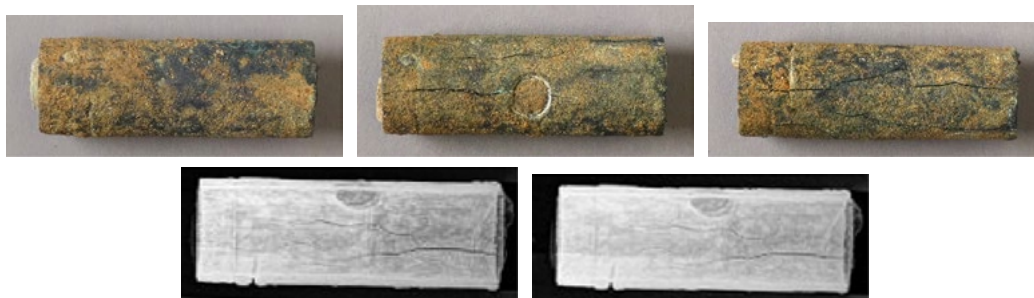
120 Tray: 10-25 W2-H-01

Lng=133, Do=14.5, E1P=1, E1T=B, E2P=1, E2T=Sm, Fe=0.1, Cu=94.1, Sn=5.9



121 Tray: 10-24 LR-07

Lng=48, Di=8.6, Do=16, H1Pos=25, H1DI=6.7, H1Dt=7.2, H1Az=0, H1BAz=-170, H1BPos=1, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.0, Cu=98.0, Sn=1.9, Pb=0.0, Sct1=6.3, Cuts=1



122 Tray: X-02 W4-01

Lng=19, Di≈8, Do=14.5-22, E1P=0, E2P=1, E2T=R, Fe=0.1, Cu=91.7, Sn=8.1



123 Tray: X-03 S1-H-01

Lng=34, Do≈14.25, E1P=0, E2P=1, E2T=Sm, Fe=0.1, Cu=97.4, Sn=2.5, Pb=0.1



124 Tray: X-04 Joined to: 088



125 Tray: X-05 S2-L-01

Lng=78, Do=15, E1P=1, E2P=0, E1T=B, Fe=1.3, Cu=94.4, Sn=4.3



140 — MUSIC FROM ANCIENT MEROË

126 Bodley: 4-09a ? S2-L-07

Lng=7, Do=14.25, E1P=1, E1T=Sm, E2P=1, E2T=Sm, L=7



127 Bodley: 5-05 Joined to: 070



128 Bodley: 5-07

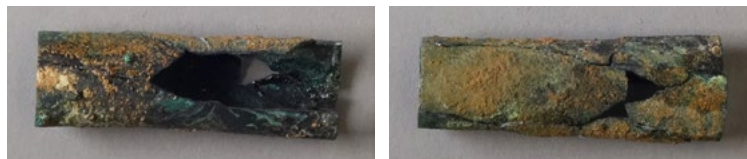


129 Joined to: 067



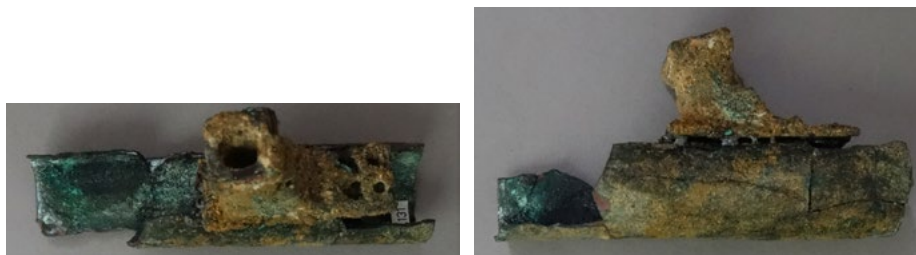
130 Tray: X-10 HL-12

Lng=52.4, Do=16, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.2, Cu=87.8, Sn=12.0



131 Tray: X-12 HR-10

Lng=64.7, Do=16, H1Pos=30.75, H1Dl=6.2, H1Dt=6.2, H1Az=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.0, Cu=93.8, Sn=6.0, Pb=0.2





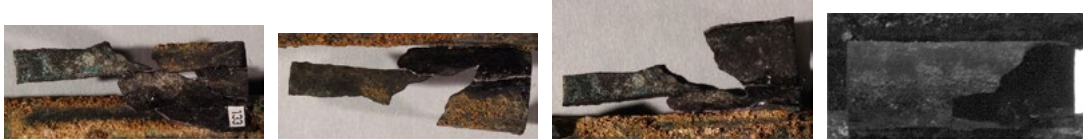
132 Tray: X-13 S2-L-02

Lng=53.4, Do=15, E1P=1, E1T=Sm, E2P=0, Fe=0.4, Cu=95.5, Sn=4.1



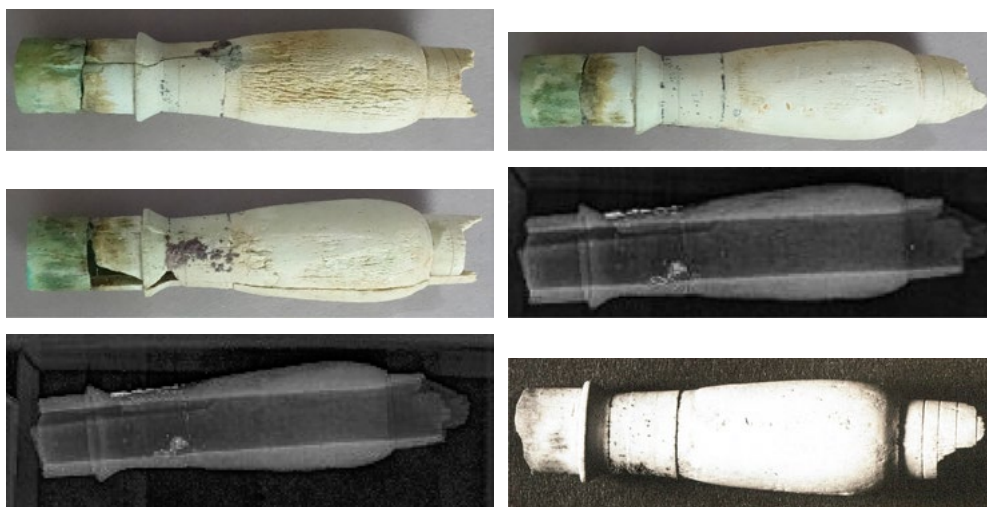
133 Tray: X-14 Bodley: 6-02b W1-L-02

Lng=37.1, Do≈15, E1P=1, E1T=Sm, E2P=1, E2T=Sm



134 Tray: X-16 Bodley: 8-01b S1-H-13

Lng=43, Di=7.4, Sp1L=17.4, Sp1D=11.5, E1P=1, E2P=1, Sp2L=9.2, Sp2D=11.1



135 Tray: X-20 HL-13

Lng=69, Di=9, Sp1L=22.3, Sp1D=14, H1Pos=-6.5, H1Dl=1.5, H1Dt=1.5, E1P=1, E2P=1, Label=L



136 Tray: X-21 LL-10

Lng=64.5, Di=9.2, H1Pos=46.9, E1P=1, E2P=1, Sp1L=2.5, Sp1D=14, Sp2L=8, Sp2D≈12



137 Tray: X-22 LR-12

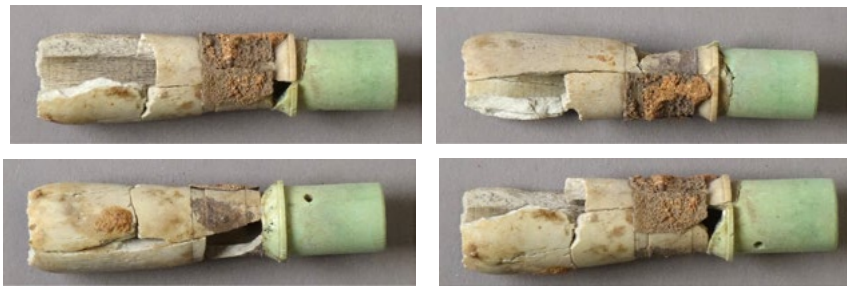
Lng=70, Di=8.6, H1Pos=52.2, E1P=1, Sp1L=20, Sp1D≈12, E2P=1, Sp2L=12, Sp2D≈12



138 Tray: X-23 HR-13
 Lng≈65, Di=9.5, H1Pos=52.3, E1P=1, E2P=1



139 Tray: X-24 S2-L-11
 Lng=43, Di=7.2, H1Pos=-3.7, H1DI=2, H1Dt=2, E1P=1, Sp1L=15.9, Sp1D=11.7, E2P=1



140 Tray: X-25 S2-H-12
 Lng=42.5, Di=7.2, E1P=1, Sp1L=17.8, Sp1D=11.65, E2P=1



141 Tray: X-26 Joined to: 067 S2-L-05
 Lng=9.4, E1P=1, E2P=1, E1T=Sm, E2T=Sm



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142 LL-04

Lng=10.8, Do=16, E1P=1, E1T=Sm, E2P=1, E2T=Sm



143 Bodley: 5-06 Joined to: 047



144 S1-L-04

Lng=42.2, Di \approx 7.5, Do=14.25, H1Pos=9.5, H1Dl=6.2, H1Dt=5.9, H1Az=0, H1BAz=-116, H1BPos=0, H2Pos=34, H2Dl=7.1, H2Dt=6, H2Az=0, H2BAz=-116, H2BPos=-5.7, H2BS=T, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=97.6, Sn=2.3, Pb=0.0, Sct1=19.5, Cuts=1



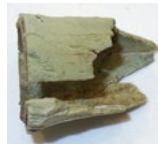
145 S2-H-02

Lng=17, Do=14.25, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.1, Cu=96.2, Sn=3.7, Pb=0.0



146 HR-15

Lng=22.2, Di \approx 9.3, Do=15-19.5, E1P=0, E2P=1, E2T=R



147

Lng=35.3, Di≈9.7, Do=15.5-23, E1P=0, E2T=R, So2D=13.3, So2L=21.6



148

Lng=23.5, H1Pos=11, H1DI=1.4, H1Dt=1.3



149 Bodley: 5-10s. Joined to: 100 HR-09

Lng=24.1



150 HR-06

Lng=20.25, Do=16, E1P=1, E1T=Sm, E2P=1, E2T=Sm



151

Lng=8.2



152 Joined to: 069 L4-06



146 — MUSIC FROM ANCIENT MEROË

153 Joined to: 115



154 Joined to: 003



155

Lng=18, H1Pos=5.5, H1DI=6.4, H1Dt=6.1, E1P=1, E1T=Sm, E2P=0



156 W1-L-08

Lng=47.85, Di=7.5, E1P=1, E2P=1, Sp1L=14.8, Sp1D=10.7-11.5



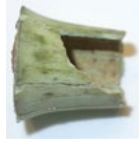
157 W2-H-06

Lng=50.3, Di=7.7, E1P=1, E2P=1, Sp1L=12.2, Sp1D=11.5, Sp2L=6.7, Sp2D≈10



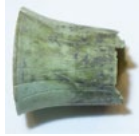
158

Lng=16, Do=15-18.1, Sct1Pos=0.5, E1P=0, E2P=1, E2T=R, Sct1=0.5



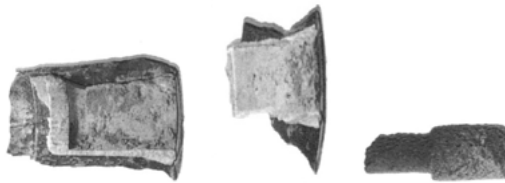
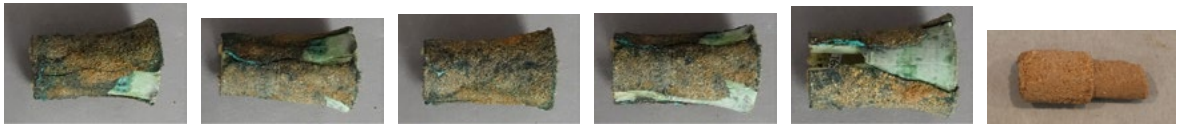
159

Lng=17.8, Do=15-17.7, Sct1Pos=1.2, E1P=0, E2P=1, E2T=R, Sct1=1.2



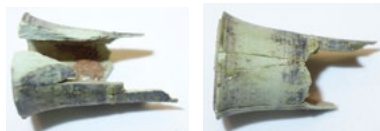
160 Bodley: 5-02 W1-L-09

Lng=25.9, Di=7.3, Do=13.6-17.3, E1P=1, E2P=1, E1T=Sm, E2T=R, Sct1=10.5



161

Lng=26, Do=14.2-17.5, Sct1Pos=11.3, E1P=1, E1T=Sm, E2P=1, E2T=R, Sct1=11.3



162

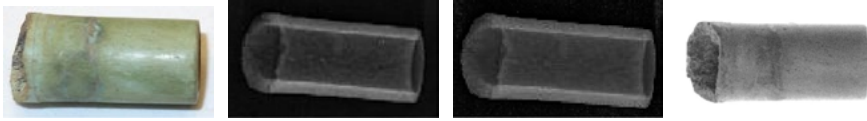


163

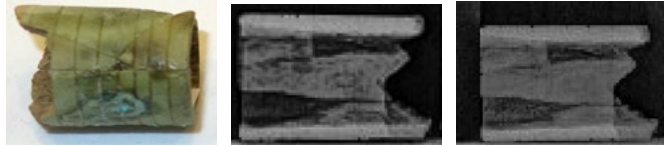


148 — MUSIC FROM ANCIENT MEROË

164 Bodley: 3-06

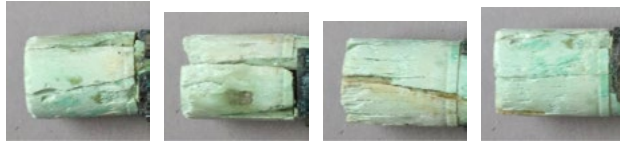


165

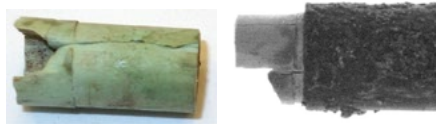


166 Joined to: 082

Lng=20.5



167 Bodley: 4-17



168



169



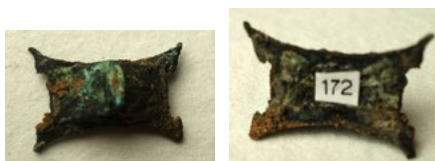
170



171 Joined to: 077 LR-08



172 Tray: 02-23? Joined to: 026



173 Joined to: 047



174 Joined to: 082



175 Joined to: 086



176 Joined to: 011



177 Joined to: 062



178 Joined to: 119



150 — MUSIC FROM ANCIENT MEROË

179 Bodley: 5-08 Joined to: 099



180 Joined to: 096



181 Joined to: 023



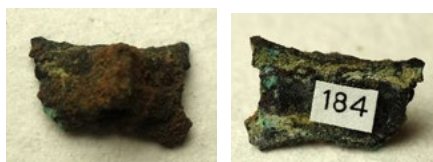
182 Joined to: 094



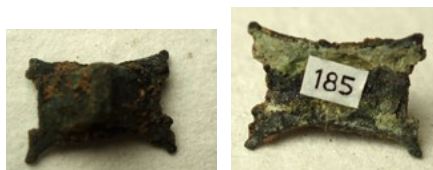
183 Joined to: 079



184 Joined to: 043



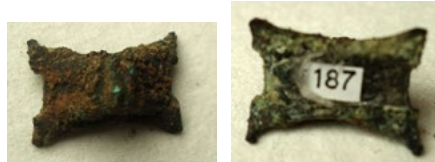
185 Joined to: 075



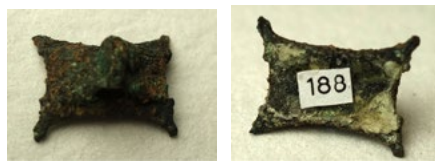
186 Joined to: 095



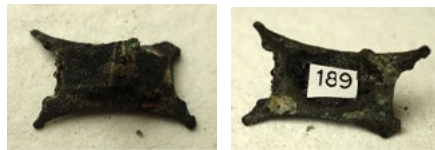
187 Joined to: 078



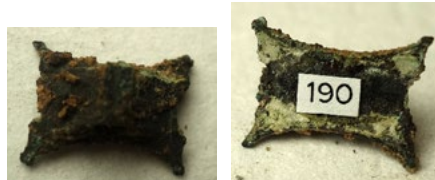
188 Joined to: 078



189 Joined to: 057



190 Joined to: 062



191 Joined to: 022



192 Joined to: 144



152 — MUSIC FROM ANCIENT MEROË

193 Joined to: 098



194 Joined to: 088



195 Joined to: 069



196 Joined to: 041



197 Joined to: 104



198 Joined to: 097



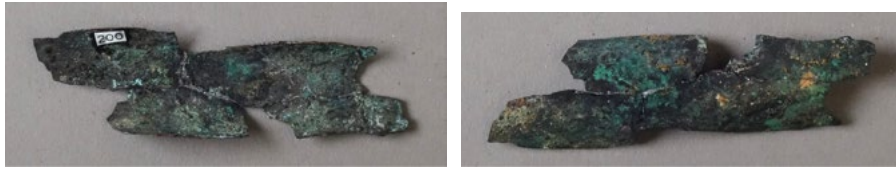
199 W1-01

Lng=24.2, Do≈20, E1P=0, E2P=1, E2T=R



200 LR-04

Lng=63, H1Pos=24, H1Dl=7, H1Dt≈7, E1P=0, E2P=0



201

Lng=8.0



202 S1-05

Lng=2.8, E1P=1, E2P=1, E1T=Sm, E2T=Sm



203 S1-H-08

Lng=3.1, E1P=1, E2P=1, E1T=Sm, E2T=Sm



204 S1-L-08

Lng=3.4, E1P=1, E2P=1, E1T=Sm, E2T=Sm



205 Joined to: 136 LL-10

Lng=5, E1P=1, E2P=1, E1T=Sm, E2T=Sm



206 HL-04

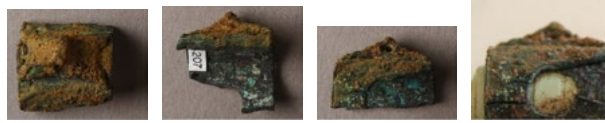
Lng=21.9, E1P=1, E2P=1, E1T=Sm, E2T=Sm



154 — MUSIC FROM ANCIENT MEROË

207 Joined to: 067

Lng=17



208 Joined to: 080



209 HR-04

Lng=51.5, Do≈16, E1P=0, E2P=1, E2T=Sm



210 S2-L-06

Lng=26.6, H1Pos=20.7, H1BAz=-80, H1BPos=-7, E1P=1, E1T=Sm, E2P=1, E2T=Sm



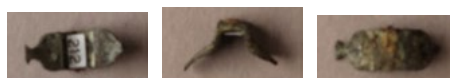
211

Lng=24.6, E1P=1, E2P=0, E1T=Sm, H1Pos=19



212

Lng≈11



213 Joined to: 050 HR-07

Lng≈11



214 Joined to: 050

Lng≈11



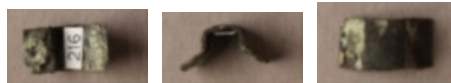
215

Lng≈11



216

Lng≈11



217

Lng≈11



218 Bodley: 5-15

Lng≈11



219 Joined to: 032

Lng≈11



220

Lng≈11



221



222



223

Lng=25.4, Do=14.8-18.5, E1P=1, E2P=1, E1T=Sm, E2T=R



224

Lng=34.5



225

Lng=23.9, Di=12.5, Do=15.8-20.9

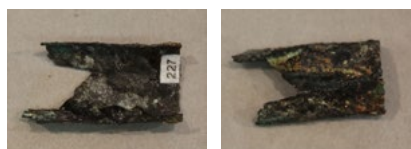


226



227 HR-05

Lng=28.4, H1Pos=29.5, E1P=1, E2P=0, E1T=Sm



228



229



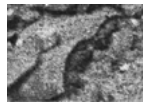
230

Lng≈23



231 S1-H-05

Lng≈7.2



232 S1-L-05

Lng=13.1, E1P=1, E2P=1, E1T=Sm, E2T=Sm



Compounds

“001”: 001+095+071+099

Lng=181.7, Di=9.55, Do=16, H1Pos=14.7, H1Dl=10, H1Dt=5.7, H1S=R, H1Az=-62, H1BS=T, H1BAz=154, H1BPos=-1, H2Pos=61.2, H2Dl=7, H2Dt=6.9, H2Az=-166, H2BS=T, H2BAz=-102, H2BPos=-5, H3Pos=109.2, H3Dl=11, H3Dt=6, H3S=R, H3Az=-111, H3BAz=-132, H3BS=T, H3BPos=0, H4Pos=152.7, H4Dl=7, H4Dt=6.9, H4Az=0, H4BAz=137, H4BS=T, H4BPos=0, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Sct1=174.7, Sct2=134.7, Sct3=130.7, Sct4=91.7, Sct5=81, Sct6=38.7, Sct7=34.2

“003”: 003+010

Lng=125, Do=16, H1Pos=14, H1Dl=6.6, H1Dt=6, H1Az=0, H1BS=T, H1BAz=127, H1BPos=7, H2Pos=55, H2Dl=6.1, H2Dt=6.1, H2Az=13, H2BS=T, H2BAz=129, H2BPos=8, H3Pos=100, H3Dl=6.1, H3Dt=6.1, H3Az=0, H3BAz=127, H3BPos=10, H3BS=R, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Sp2L=20, Sp2D=14, Sct1=83.5, Sct2=78.5, Sct3=39.5

“004”: 114+004

Lng=77.5, Do=14.25, H1Pos=27, H1Dl=6.5, H1Dt=5.4, H1Az=0, H1BS=T, H1BAz=-110, H1BPos=1, H2Pos=68.7, H2Dl=6.7, H2Dt=4.9, H2Az=0, H2BS=T, H2BAz=-105, H2BPos=-1, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Fe=0.2, Cu=99.1, Sn=0.7, Pb=0.0, Sct1=56.8, Sct2=37.5, Sct3=15.3

“041”: 087+096+098+009+041

Lng=218.5, Do=16, H1Pos=14.25, H1Dl=10.5, H1Dt=6, H1S=R, H1Az=0, H1BAz=160, H1BPos=2, H1BS=T, H2Pos=61, H2Dl=8.5, H2Dt=6.9, H2Az=63, H2BAz=-100, H2BPos=3.5, H3Pos=108.75, H3Dl=10.5, H3Dt=6, H3S=R, H3Az=0, H3BAz=160, H3BPos=-3.5, H3BS=T, H4Pos=159, H4Dl=12, H4Dt=6, H4S=R, H4Az=0, H4BAz=160, H4BPos=-9.5, H4BS=T, E1P=1, E1T=Sp, Sp1L=19.5, Sp1D=*13, E2P=1, E2T=Sp, Sp2L=10, Sp2D=*14, Sct1=170.2, Sct2=133.5, Sct3=128, Sct4=89.5, Sct5=80.5, Sct6=43.8

“067”: 079+080+067

Lng=134.8, Do=14.25, H1Pos=14.4, H1Dl=*6.3, H1Dt=*6.3, H1Az=0, H1BAz=120, H1BPos=-1.5, H1BS=T, H2Pos=35.5, H2Dl=6.3, H2Dt=6.3, H2Az=0, H2BAz=120, H2BPos=0.5, H2BS=T, H3Pos=56.3, H3Dl=*8, H3Dt=5.9, H3Az=0, H3BAz=120, H3BPos=0, H4Pos=72.5, H4Dl=6.3, H4Dt=6.2, H4Az=0, H4BAz=120, H4BPos=0, H5Pos=108.7, H5Dl=7, H5Dt=6, H5Az=6, H5BAz=120, H5BPos=-3.5, H5BS=T, H6Pos=125.7, H6Dl=6.6, H6Dt=6.05, H6Az=0, H6BAz=120, H6BPos=2, H6BS=T, E1P=1, E1T=Sm, E2P=1, E2T=Sm, Sct1=117.4, Sct2=92, Sct3=82.5, Sct4=64.6, Sct5=45, Sct6=24

“086”: 082+086

Lng=88.3, Di=*8.9, Do=16, H1Pos=16.5, H1Dl=11, H1Dt=5.5, H1S=R, H1Az=0, H1BAz=122, H1BPos=1, H1BS=T, H2Pos=53, H2Dl=7.4, H2Dt=7.4, H2Az=0, H2BAz=119, H2BPos=0, H2BS=T, E1P=1, E1T=Sm, Sp1L=20.5, Sp1D=14, E2P=1, E2T=Sm, Sct1=68.7, Sct2=35

6 Material Analysis

*Richard Newman, Susanne Gänsicke, Joel Stephenson, Caroline Cartwright,
Daniel Kirby*

6.1. Introduction, *Richard Newman and Susanne Gänsicke*

The pipes were made from a small range of materials, as described in chapter 4, mainly copper alloy(s), bone, and wood, with occasional use of silver. Textile remnants have also been found. All these materials have been characterized as best as possible, using noninvasive techniques and analysis of a limited number of samples (figs. 6.1–2).

The results are discussed in this chapter. It appears, from limited analyses, that the copper alloy utilized was a tin bronze that in some instances contained no lead, while in other instances some lead was probably a part of the original composition. In bone parts, a few analyses have indicated mammalian bone.

All pipes have solid outer walls of copper-alloy tubing, their full lengths formed by combining several sections of this tubing. The inner tubing was partially made from bone and partially from wood; in some pipes, sections of both materials were used. In most sections with a bone core, double wall bronze tubes with rotary outer sleeves were used. The narrowing neck of some bulbs was decorated with a thin layer of silver.

Smaller parts were attached with solder. The turning sleeves are furnished with separately made knobs of varying shapes (see ch. 5 for further discussion). The externally applied long sliders ending in dolphin shapes are held in place by narrow bronze strips (which are referred to as slider guides). Three “chimneys” were added to the outer wall of some tubes (see ch. 5).

The diversity of mechanical systems within the group is surprising and of great interest, as some of the parts display unique features amongst known auloi. To understand the instruments fully, it is of critical importance to study the nature of the materials used in their manufacture, how these materials were manipulated to allow their mechanical shaping, and what techniques were used to create the different tube sections and smaller, externally applied features that served a practical or decorative purpose.

In the following, we will identify the basic materials and describe how individual sections were formed, even though numerous questions will have to remain unanswered at this time. Knowledge of the mechanical systems also informs us on how the pipes may have been handled and played, and the information gleaned will, in the end, be essential in creating playable replicas.

6.2. X-Radiography, *Susanne Gänsicke and Richard Newman*

Metal parts were twice examined by X-radiography (figs. 6.3–7). First, a select number of sections were radiographed using traditional X-ray film; these items were removed from their boxes and arranged on the film for an initial cursory examination.¹ A second, more comprehensive round used computed radiography (CR) to capture the metal-containing fragments and some of the bone pieces in their new temporary storage boxes (fig. 6.3).²

1. Figure 6.5: X-ray # 1593. Exposure: kV 110, mA 3.0, Exp. 2.0 mins. 2/14/2014.

2. Figure 6.3: X-ray # 1625, tray 3, view 1. Exposure: kV 110, mA 3.0, Exp. 2.0 mins, focal spot 5.5. 6/9/2014. Figure 6.4: X-ray # 1627, tray 11, view 2. Exposure: kV 110, mA 3.0, Exp. 2.0 mins, focal spot 5.5. 6/12/2014. Figure 6.6: X-ray # 1627, tray 10, view 1. Exposure: kV 110, mA 3.0, Exp. 2.0 mins, focal spot 5.5. 6/12/2014. Figure 6.7: X-ray # 1627, tray 12, view 1. Exposure: kV 110, mA 3.0, Exp. 2.0 mins, focal spot 5.5. 6/12/2014.



Figure 6.1 . Peter Holmes at the Museum of Fine Arts, Boston, in May 2015. SC 323875. Photograph © Museum of Fine Arts, Boston.

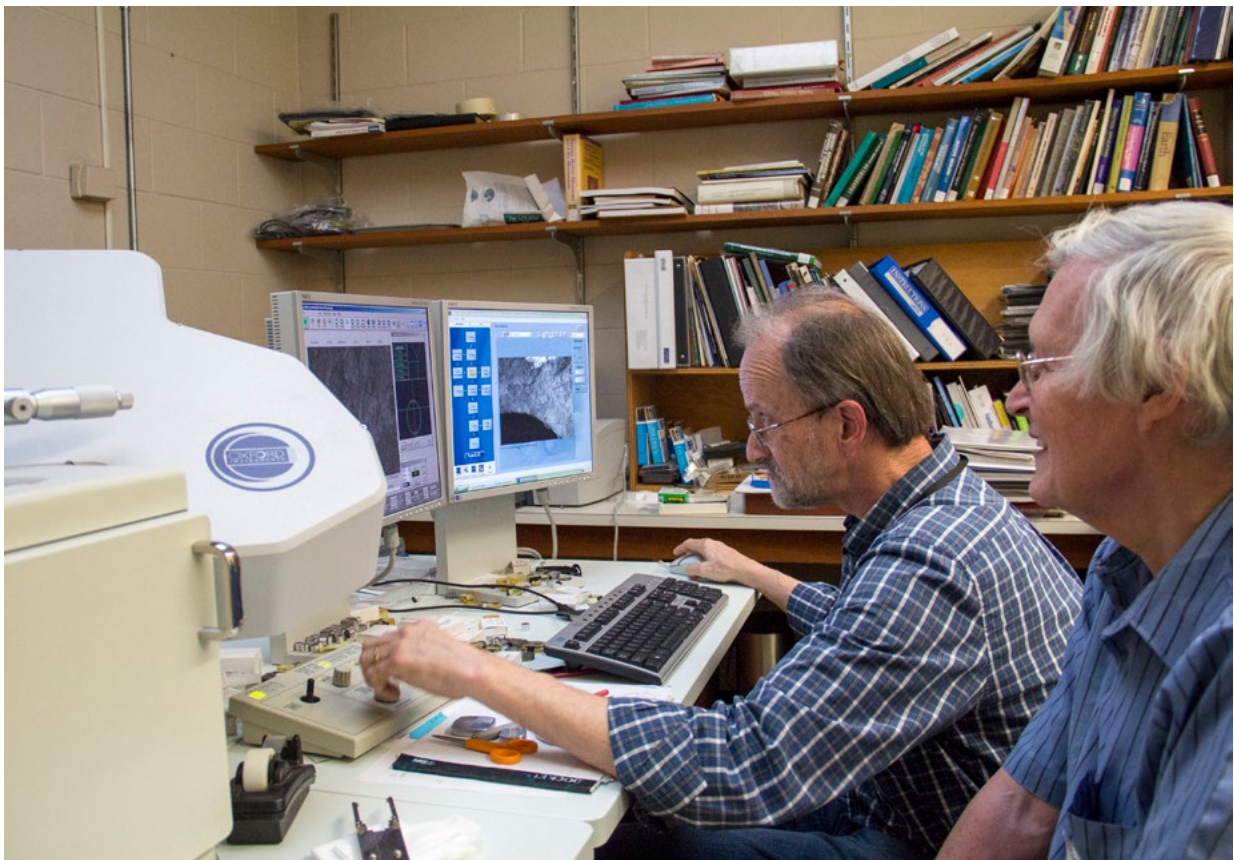


Figure 6.2. Richard Newman and Peter Holmes in the SEM laboratory of the Museum of Fine Arts, Boston in May 2015. SC 323849. Photograph © Museum of Fine Arts, Boston.



Figure 6.3. Digital X-radiograph of rehousing aulos sections from the original wooden storage tray 3, including the dolphin-shaped sections. X-ray # 1625, tray 3, view 1. Exposure: kV 110, mA 3.0, Exp. 2.0 mins, focal spot 5.5. 6/9/2014.

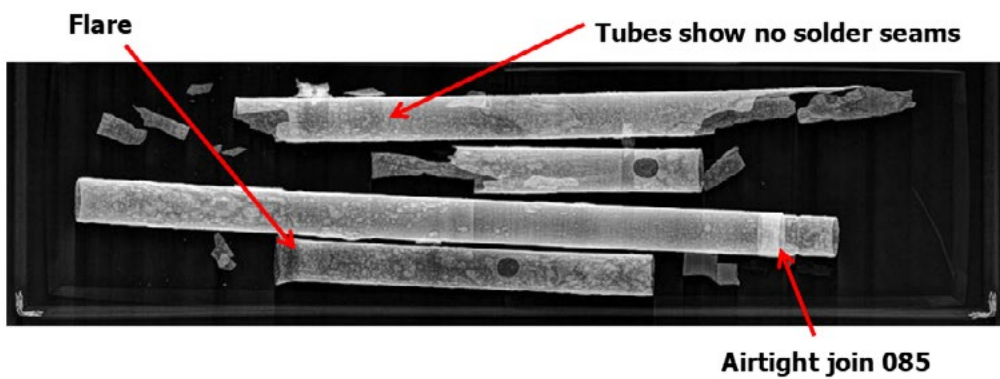


Figure 6.4. Digital X-radiograph of rehousing aulos sections from the original wooden storage tray 11, showing longer tubes without seams, hammered out flares, and item 085. X-ray # 1627, tray 11, view 2. Exposure: kV 110, mA 3.0, Exp. 2.0 mins, focal spot 5.5. 6/12/2014.

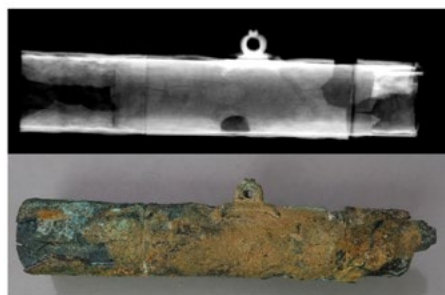
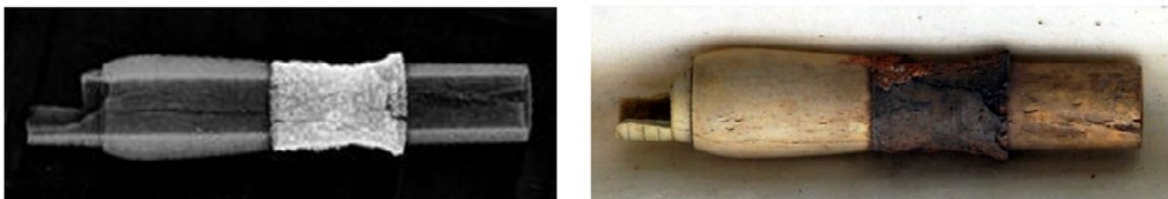


Figure 6.5. Film X-radiograph of item 072 and its photograph, displaying the thin layers of bronze tube sections inserted into each other. X-ray # 1593. Exposure: kV 110, mA 3.0, Exp. 2.0 mins. 2/14/2014.



Figure 6.6. Digital X-radiograph of rehousing auloi sections from the original wooden storage box 10, showing a number of sections with intentional cuts, as well as tubes sections with knobs. X-ray # 1627, tray 10, view 1. Exposure: kV 110, mA 3.0, Exp. 2.0 mins, focal spot 5.5. 6/12/2014.



111

Figure 6.7. Digital X-radiograph of bulb 111 and its photograph, displaying the straight bore and the radio opaque mineralized silver sleeve. X-ray # 1627, tray 12, view 1. Exposure: kV 110, mA 3.0, Exp. 2.0 mins, focal spot 5.5. 6/12/2014.

In the images, several features and material characteristics can be observed. The mottled, heterogenous nature of the bronze tubes is the result of different degrees of mineralization. The generally blotchy nature of the tubes therefore was caused by corrosion, which led to uneven loss of metallic substance.

It came as a surprise to us that none of the straight tube sections show seams, neither the short nor the comparatively long tubes of up to 27 cm. The lack of seams has important implications for the interpretation of the original manufacture. Flares appear to have been hammered out, as the metal is less radiopaque than the tube from which they emerge (fig. 6.4).

The radiographs also provide insight into the highly sophisticated fine mechanics of the auloi: uniform sections of extremely thin and straight bronze tubing (mostly about 0.3–0.4 mm in wall thickness) were fitted into each other to form an airtight system (fig. 6.5). Like in other aulos finds, external diameter is basically homogenous throughout an instrument.

Another interesting feature, initially discovered in the radiographs as dark lines, are straight slits or cuts on many short tubes, where thin partial rings were intentionally cut from the tube's end (fig. 6.6).³ These presumably mechanical features are so far unique to the Meroë doublepipes. Although we develop hypotheses about their function in chapter 5.2.1.5, these remain to be verified by experimental reconstruction.

The bone bulbs display straight internal bores, and the remnants of their thin silver sleeves show up as radio-opaque (see fig. 6.7).

CT scanning was carried out in February 2014 by Rajiv Gupta at Massachusetts General Hospital, but failed to produce usable information.⁴ This was probably due to the specific resolution of the equipment used in the medical field when compared with the standard radiography that had already been carried out.

6.3. Alloy Analysis, *Richard Newman*

Copper alloy (bronze) was used in thicker cast items, thin turned tubes, and slider guides. Thin silver sheet was used as local decoration, applied to narrow sections of bone tubes. Visual observation had suggested that selective tinning could have been used on slider ends and perhaps elsewhere. Cast elements were attached to tubes with solder, and analyses suggest that the solders were lead-tin alloys.

6.3.1. X-Ray Fluorescence Analysis

Some elements were analyzed with a Bruker Artax micro-X-ray fluorescence spectrometer (XRF). The instrument has a rhodium tube, which was operated at 40 kV, 400 μ A, with 60-second acquisition time. The beam diameter is 0.65 mm. Numerous points along the lengths of pipe fragments both of larger and smaller diameter were analyzed, and relative amounts of copper, tin, lead and iron calculated for each point utilizing a lab bronze standard (a full description of the different types of pipes is given in ch. 7). From a quantitative point of view, information from these analyses is of limited utility due to the extensive corrosion of most metallic parts. Qualitatively, however, the results provide some indication of the original alloys of the parts. Lead was not detected above a trace level in any part. Iron was usually detected in trace amounts; its presence could be in accretions just as well as in corrosion products or in the copper alloy. The alloy of every part analyzed was bronze—the tin content appears to be well under 10 percent, but there is considerable variation in the calculated amount of this element from point to point, which must in great part be attributed to the effects of corrosion. Overall, such copper alloys were a common type found in a variety of Roman-era copper alloy objects.⁵ Points with particularly high amounts of tin possibly indicate remnants of tinning. One point on a small-diameter fragment contained very high lead and tin, and this point was probably located on an area of solder.

6.3.2. Scanning Electron Microscopy/Energy-Dispersive X-Ray Spectrometry (SEM/EDS)

Some sixteen fragments of the auloi were directly examined in a JEOL JSM-6460LV scanning electron microscope with an attached Oxford Instruments X-MaxN energy-dispersive X-ray spectrometer, operated by INCA software (SEM/EDS). Additional examinations were carried out in a JEOL JSM-IT500 LV SEM, with the same X-ray spectrometer operated by AZtec software. Objects were examined in low-vacuum mode, at 20 kV with a beam current of ca. 1 nA. Quantitative analyses were carried out using default Oxford metal standards. As in the case of the XRF analyses, it is difficult to discern original metal compositions from the SEM/EDS analyses of parts, as bare unaltered metal is rarely seen. However,

3. Sutkowska 2015: 417.

4. Rajiv Gupta, MD, PhD, at that time Director, Ultra-High Resolution Volume CT Lab, Massachusetts General Hospital and Harvard Medical School.

5. Riederer 2000, 2002.

since very small regions (as small as a few micrometers) can be analyzed, the SEM/EDS examinations can provide more information than could be gleaned from the XRF analyses.

The most reliable quantitative analyses of bronze elements were carried out on two sets of polished metal cross sections: a complete section of one tube (discussed here and in the following paragraphs), and a few small metal fragments, probably also from tubes. These few analyses of course are unlikely to represent the compositions of alloys used in all parts of the auloi.

Analyses of parts that were carried out in the SEM suggest that the copper alloys utilized were bronze with a relatively low tin content, although that content may vary somewhat from element to element.⁶ Some lead was probably an intentional part of the bronze used in certain elements but is essentially absent in others. Solder remnants were present on several items, and these residues present difficulties in determining tin (and lead) contents of the surrounding bronze alloys, as the solders consist of mixtures of lead and tin.⁷ Another complication is the apparent presence of tinning on some pieces. Tinning would have been carried out by rubbing a semimolten piece of tin over the surface of the substrate metal.⁸ The surface would have a distinctly silvery appearance, contrasting with the bronze-colored substrate. As the applied tin layer would have been quite thin and well-adhered to the substrate, partly by diffusion of tin into the bronze, the presence of tinning cannot be easily discerned by the direct examination. Unexpectedly elevated levels of tin could point to the presence of tinning, particularly if no (or negligible) lead is detected, as the latter would be present in relatively high amounts if the detected tin is due to remnants of solder. Due to corrosion, the tin content of a bronze alloy, if only surface analysis is carried out (as in SEM examinations), can appear to be higher than it actually was in the original alloy. Higher-than-expected tin contents thus could be due to more than one cause, and the true explanation for the high level may be uncertain.

In the following, some findings from the SEM/EDS examinations are discussed.

6.3.2.1. *Front and back sides of slider 051*

A detail from the backside (fig. 6.8) shows accretions (darker gray) and corrosion (light gray). There are patches of relatively bare metal that show very sharp tool marks (mostly running vertically) from surface manipulation during original manufacture; little corrosion can have taken place in these regions.

6.3.2.2. *Knob 175*

Nearly bare metal can be seen in places, between filament-like accretions that contain calcium and are probably oxalates (fig. 6.9). The metal, which shows faint striations running nearly vertically, has a composition of about 80 percent copper, 11 percent tin and 4 percent lead. Although there is solder elsewhere on the knob (fig. 6.10), the alloy of this knob almost certainly contains a small amount of intentionally added lead. The presumed remnant of solder contained 54 percent tin, 28 percent lead, 18 percent copper (the latter from the substrate alloy).



Figure 6.8. Backside of slider 051, back-scattered electron photomicrograph taken in a scanning electron microscope.

6. Pelosi et al. 2016; Bougarit 2025

7. Pelosi et al. 2016; Lopes et al. 2018.

8. Giumlia-Mair 2020.

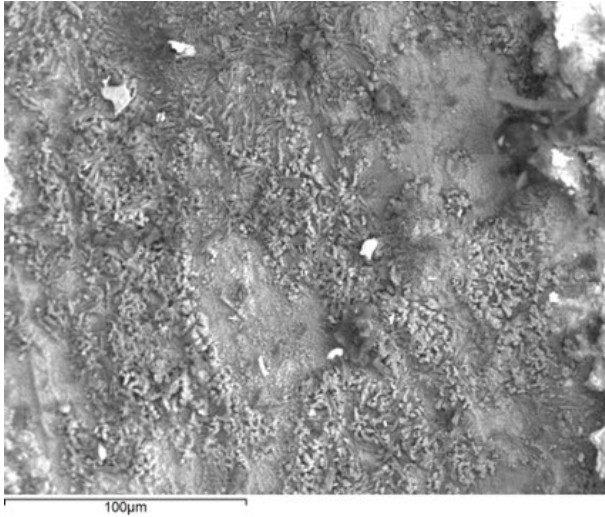


Figure 6.9. Knob 175, almost bare metal and accretions, back-scattered electron photomicrograph taken in a scanning electron microscope.

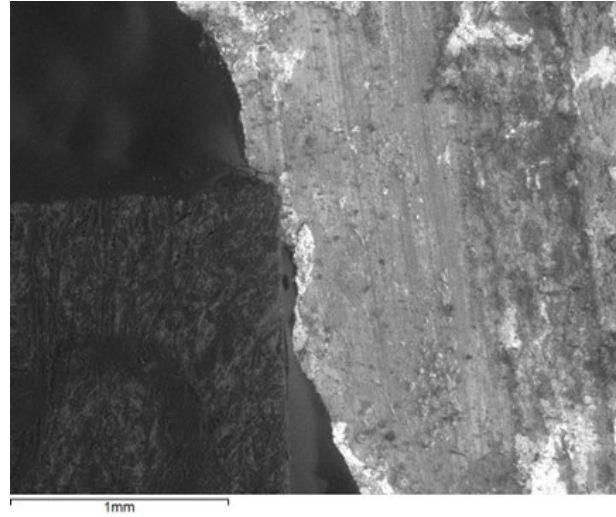


Figure 6.10. Knob 175, solder traces, back-scattered electron photomicrograph taken in a scanning electron microscope.

6.3.2.3. Spacer ring 126

A very short tube (“spacer ring”) (126) was chosen to prepare a polished cross section. The tube was mounted in epoxy resin, then cut in half with a low-speed diamond cutoff saw. Its polished cross section contains many regions of uncorroded metal (fig. 6.11). The inner surface in this detail contains a thick layer of corrosion (at bottom of figure), while little corrosion is present on the outer surface (top of figure). In a more highly magnified view of a part of the outer surface (fig. 6.12), a thin (20 μm) layer of corrosion products (at the left side of the image)—porous at the top, more compact lower down—lies on top of some loosely packed particles of dirt, below which is the uncorroded metal substrate (on the right side of the image). The more compact, lower part of the corrosion layer contains about 23 percent tin, in contrast to approximately 11 percent in the nearby substrate. This may represent a remnant of tinning. As discussed below (ch. 6.4), there appears to be redeposited copper at the top of the corrosion layer.



Figure 6.11. Spacer ring 126, part of polished cross section, back-scattered electron photomicrograph taken in a scanning electron microscope. Thickness of metal about 380 μm .

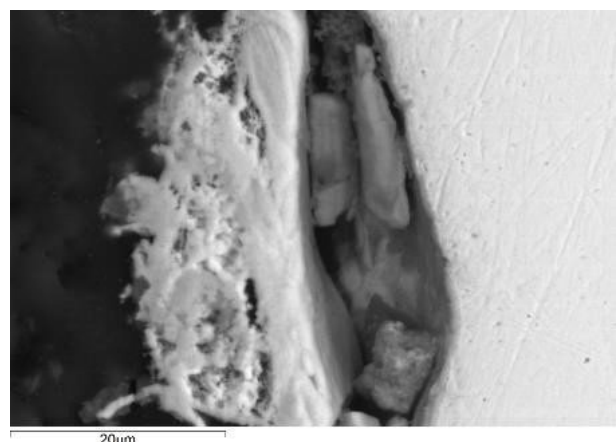


Figure 6.12. Detail of outer surface of spacer ring 126, polished cross section, back-scattered electron photomicrograph taken in a scanning electron microscope.

6.3.2.4. Tube 089 (originally bearing chimney 090)

Some of the surface contained heavy deposits of accretions—probably mainly calcium carbonate, quartz and other silicates (fig. 6.13). There were small areas of visible metal substrate that contained very high amounts of tin (tin weight percent greater than copper weight percent), with no detectable lead, almost certainly indicating the presence of tinning. No regions on the surface contained substantial lead, which suggests that no solder is present, although it is likely that the now-detached chimney was originally held in place with solder. Examination of the detached chimney (090) found many regions near the part that was attached to the tube in which lead and tin contents were quite high (tin ranging from 17–28 percent, lead from 20–25 percent, remainder copper from the substrate).

6.3.2.5. Bare metal patch on 003

The patch appeared to be relatively uncorroded and showed very clear striations from likely original surface manipulation, perhaps turning marks. Analyses showed unexpectedly high tin (16–25%) and lead (5–12%) contents. This may reflect the fact that a knob had been soldered at this position and solder on the surface skewed the results. Its recent detachment had exposed the uncorroded patch on the tube.

6.3.2.6. Silver sleeve from bone bulb

Only one part with silver was examined (214), and in this case the metal was extremely corroded; all that could be detected were corrosion products (silver chloride and some silver bromide, with some silver sulfide).

6.4. Metallography, Richard Newman and Susanne Gänsicke

Both halves of the cut spacer ring 126 were polished, and one was etched. Both unetched and etched halves were examined by reflected light microscopy and scanning electron microscopy. SEM/EDS analysis, as noted in ch. 6.3.2.3, indicated that the tube was made from bronze with a composition of about 90 percent copper and 10 percent tin.⁹

Etching of the tube revealed a highly stressed metal structure (fig. 6.15), indicating coldworking and annealing during manufacture.¹⁰ Based on this observation, it is assumed that this seamless tube was cast from bronze and further shaped by mechanical means. While hammering may have been employed during initial shaping of the tubes, their apparently quite thin and even thickness suggest that turning and lathe work were used for the fine finishing, with annealing to relieve stresses from the cold working procedures, as indicated by the recrystallization and twinning seen in the single metallographic section. One might

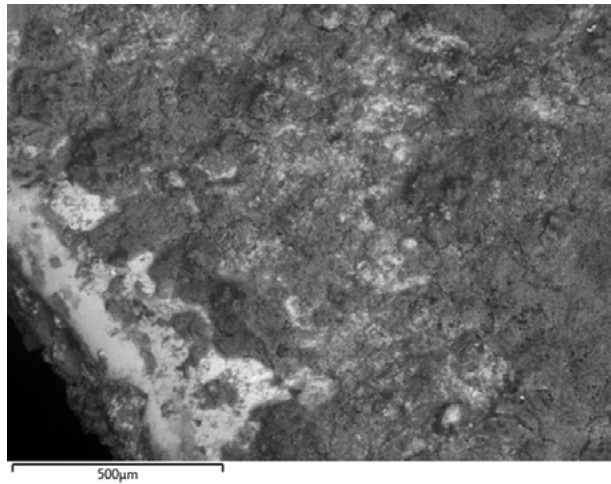


Figure 6.13. Tube for chimney 089, back-scattered electron photomicrograph taken in a scanning electron microscope.

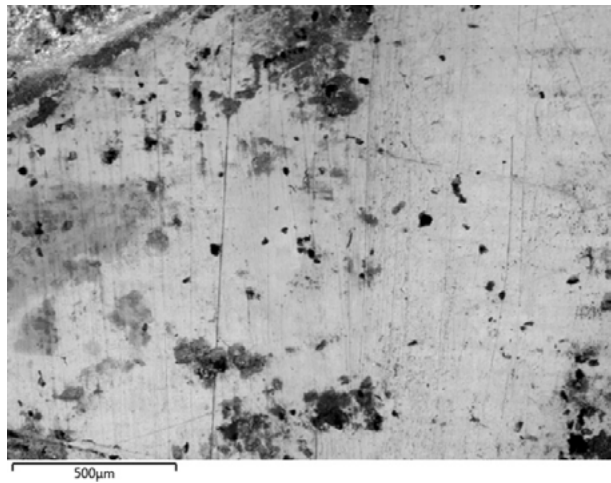


Figure 6.14. Bare metal patch on section 003, back-scattered electron photomicrograph taken in a scanning electron microscope.

9. Byrne 2000: 282, quotes the alloy of the C2AD aulos from London as 91% copper and 9% tin.

10. Scott 1991: 72, Alcoholic ferric chloride: 120 mL ethanol C₂H₅OH; 30 mL hydrochloric acid HCl; 10 g ferric chloride, FeCl₃.



Figure 6.15. Bright-field reflected light photomicrograph of polished and etched cross section of spacer ring 126. Width of field 1.2 mm.

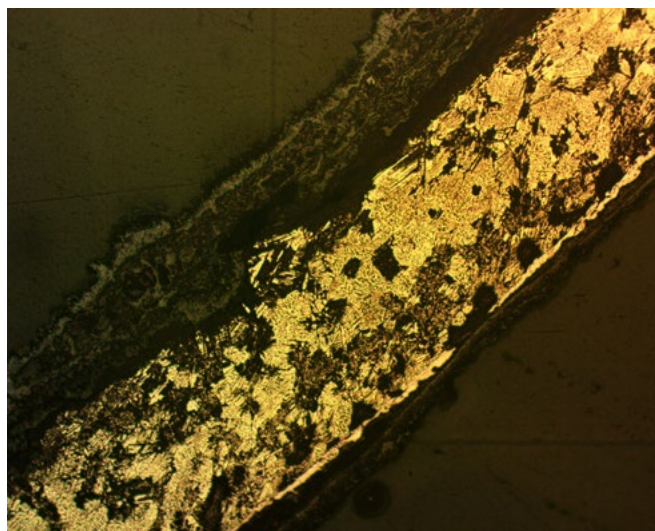


Figure 6.16. Bright-field reflected light photomicrograph of polished and etched cross section of spacer ring 126, showing thin layer of redeposited copper on surface at right. Width of field: 1.3 mm.

assume that longer straight tubes were created and subsequently cut into sections as required. This short tube was sacrificed for analysis; unfortunately, its special nature must caution us from applying insights gleaned about its production to all other bronze tubes. The question of tube manufacture certainly requires further detailed study.

Also of interest is a thin layer in places on the outer surface, whose reddish color on the polished cross section suggests it may be redeposited copper.¹¹ The layer is visible in the brightfield reflected light image (fig. 6.16) and a highly magnified SEM image of the cross section (fig. 6.12). SEM/EDS analysis confirms that this discontinuous layer consists of nearly pure copper. It is underlain and disrupted in many places by corrosion products.

6.5. Corrosion Analysis, *Richard Newman and Susanne Gänsicke*

Two thousand years of burial in the desert sand of the northern Sudan did not serve the thin-walled metal tubes well. As discussed in chapter 4, the bronze displayed extensive corrosion and mineralization, although even within short sections of tubing, the condition of the metal could be fully mineralized in one area and still display a metallic surface a short distance away. Corrosion patterns could be thin and compact, with raised pustules, or expanded and cracked.¹² Colors range visually from expected copper corrosion products such as red cuprite, shades of green for copper carbonates, lighter greens for assumed copper chloride (desert sand often contains traces of soluble salts) to local eruptions of turquoise crystals, while the interior of many tubes also displays a richer turquoise color. Sixteen samples were removed with a scalpel from selected tube sections in an attempt to retrieve representatives of observed degradation products, and to investigate if the inner surfaces had corroded in a different manner from the exterior.

11. Wang and Merkel 2001; ; Scott 2002: 85.

12. Robbiola, Blengino, and Fiaud 1998; Scott 2002.

6.5.1. Analytical Protocol

All metallic fragments were at least partially covered with corrosion products. Most often these were green or bluish green in color, less frequently red or nearly black. Sixteen samples were taken from nine fragments for general identification (table 1).

Table 1. Samples of corrosion products taken for analysis.

Sample	Inventory	Description
1	066	Raised bright green corrosion eruption on exterior
2	066	Blue green corrosion on interior, likely formed in contact with internal bone tube, now lost
3	066	Black dense corrosion "grain" on exterior
4	113	Blue green at border of white patch
5	113	White patch, dense, almost shiny
6	036	Matte black, raised, velvety
7	036	Grayish corrosion, appears to be related to trace of solder that once held a slider guide
8	036	Turquoise/dense, not raised, along straight line, perhaps caused by contact with slider
9	024	Bright cold colored green, raised corrosion
10	005	Darkish turquoise corrosion on inner bronze sleeve
11	005	Medium colored, warm green, slightly granular
12	008	Dark green, compact corrosion
13	179	Turquoise, soft corrosion on top of ridge
14	179	Dense matte black corrosion
15	080	Red corrosion covered with thin darker layer
16	080	Turquoise corrosion

Small pieces of each sample were pressed between two diamond windows and analyzed by transmission Fourier transform infrared microspectroscopy (M-FTIR) using a Thermo Nicolet s10 FTIR with attached Continuum IR microscope. 100 scans at 4 cm⁻¹ resolution were collected in the 4000–650 cm⁻¹ range. Identifications of compounds were made by searching in-house libraries and the Infrared and Raman Users Group (IRUG) digital database, 2007 edition. In general, IR analysis can specifically identify copper corrosion products that contain polyatomic ions (carbonates, sulfates, phosphates, etc.). Common basic chloride corrosion products can also be identified. Oxides and sulfides cannot be identified by mid-IR spectroscopy.

In mixtures, compounds present at a level of less than about 20 percent cannot usually be detected by IR spectroscopy. Since corrosion products on copper alloys may be mixtures of more than one compound, the analyses carried out here should not be considered to fully characterize any given sample.

Table 2 summarizes the compounds that were identified or tentatively identified.

Table 2. Compounds identified or tentatively identified in corrosion samples.

Inventory (sample)	Components identified	Possible additional components
066 (1)	atacamite, paratacamite	
066 (2)	atacamite	carbohydrate
066 (3)	aragonite	silicate, carbonate, hydrocarbon wax, witherite

Table 2, *continued*

Inventory (sample)	Components identified	Possible additional components
113 (4)	weddellite, calcite, microcrystalline wax	
113 (5)	calcite, microcrystalline wax	fatty acid salt
036 (6)		cuprite*
036 (7)	whewellite	hydrocarbon wax
036 (8)	calcium oxalate, calcite, aragonite	hydrocarbon wax
024 (9)	atacamite, paratacamite	
005 (10)	calcium oxalate	
005 (11)	calcium oxalate, kaolinite	
008 (12)	paratacamite, kaolinite	
179 (13)	silicate (not quartz or kaolinite)	
179 (14)	silicate (not quartz or kaolinite)	
080 (15)	atacamite, paratacamite	calcium oxalate
080 (16)	paratacamite	

*Sample is red in color and essentially opaque by polarizing light microscopy, assumed to be cuprite.

6.5.2. Discussion of the Results

Commonly identified were atacamite and paratacamite, often both in the same sample.¹³ These copper oxychlorides, which can be indicative of active corrosion, presumably imply that chloride-containing salts were in contact with parts of the auloi in their burial environment.

Oxalates, which in some cases could be specifically identified as weddellite or whewellite, were found in several samples. Oxalic acid presumably originated from biodeterioration of organic components of the auloi—possibly their bone elements.

Numerous compounds detected or tentatively identified originate from surrounding soil and are not products of deterioration of any of the aulos components.

In a few samples, material or materials that appear to contain saturated hydrocarbons were at least tentatively identified, mainly on the basis of very sharp absorption bands in the C-H stretching and bending region (3000–2800 cm⁻¹). As no known previous restoration has been carried out on these items, it is difficult to understand the significance of the presence of such material(s).

As discussed earlier, several parts were examined in a scanning electron microscope with an attached energy-dispersive X-ray spectrometer (SEM/EDS), and some prepared metallographic samples were also studied (see chs. 6.3 and 6.4). These examinations indicated that the major corrosion products on all bronze parts were copper chlorides. Most parts also contained areas of calcium-rich accretions, which may have included calcite from soil. Calcium-rich areas often appeared to be made up of intertwined filaments. This could indicate that these areas contained calcium oxalate(s). SEM/EDS analyses showed the presence of copper phosphate(s) in some areas. Although quite minor with respect to chlorides, the phosphates could have formed through reaction with nearby bone parts.

13. See also Schiattone et al. 2024 on corrosion studies of Roman pipes from Pompeii.

6.6. Radiocarbon Dating, *Richard Newman*

Two small wood samples were selected for radiocarbon dating.¹⁴ Both were featureless splinters, which were deemed worthy of sacrifice, as the analysis would lead to their complete destruction. They were removed from tray 2 and tray 12 A.



Rafter Radiocarbon Calibration Report

NZA 58779

R 40690/1

Report issued: 7 Apr 2015

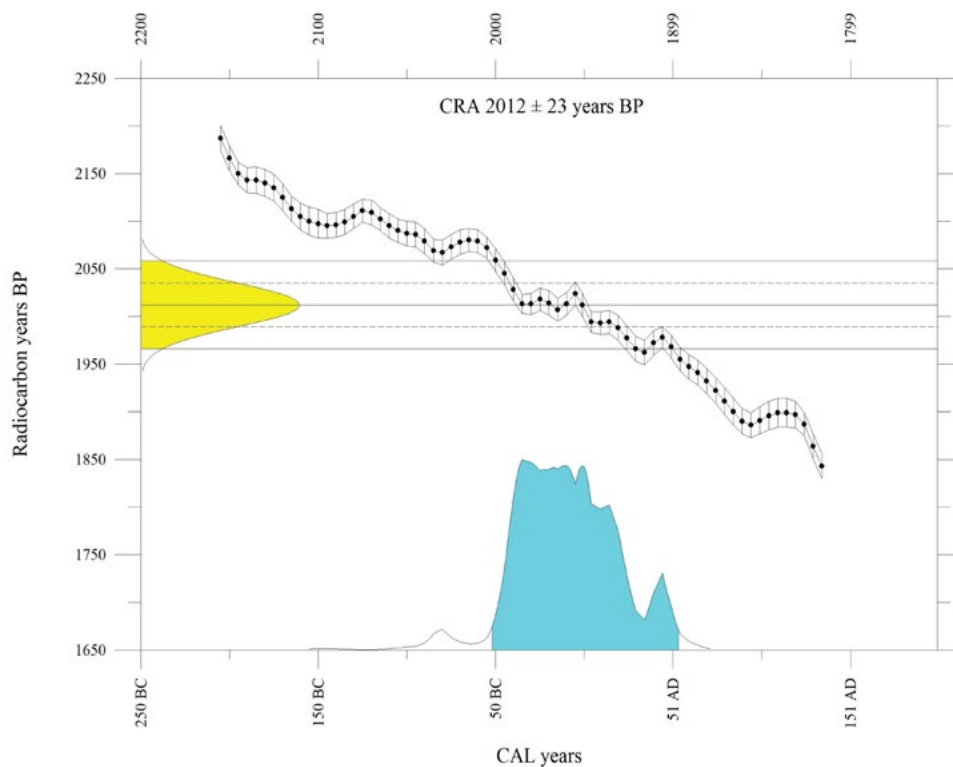
CONVENTIONAL RADIOCARBON AGE 2012 ± 23 years BP

Calibrated with IntCal13 (Reimer et al., Radiocarbon 55(4):1869-1887, 2013).

CALIBRATED AGE in terms of confidence intervals

1 sigma interval is 40 BC to 16 AD 1989 BP to 1934 BP (67.0% of area)

2 sigma interval is 52 BC to 54 AD 2001 BP to 1896 BP (94.9% of area)



Calibration performed using Winscal v. 6.0 adapted from: Stuiver and Reimer (*Radiocarbon* 35(1): 215-230, 1993).

National Isotope Centre, GNS Science
PO Box 31-312 Lower Hutt, New Zealand Phone +64 4 570 4644
Email radiocarbon@gns.cri.nz Website www.RafterRadiocarbon.co.nz


Figure 6.17. Calibration report from radiocarbon analysis of sample T2 (from original wooden storage tray 1).

14. Hajdas et al. 2021.

6.6.1. Sample Preparation

The two samples were analyzed by Rafter Radiocarbon, National Isotope Centre, GNS Science, PO Box 31-312 Lower Hutt, New Zealand.

Chemical pretreatments involved organic solvent washes in a soxhlet extractor, followed by acid/alkali/acid washes to isolate cellulose. The solid samples were converted to carbon dioxide by combustion in an elemental analyzer, then carbon dioxide was converted to graphite by reduction with hydrogen over iron catalyst.



Rafter Radiocarbon
Calibration Report

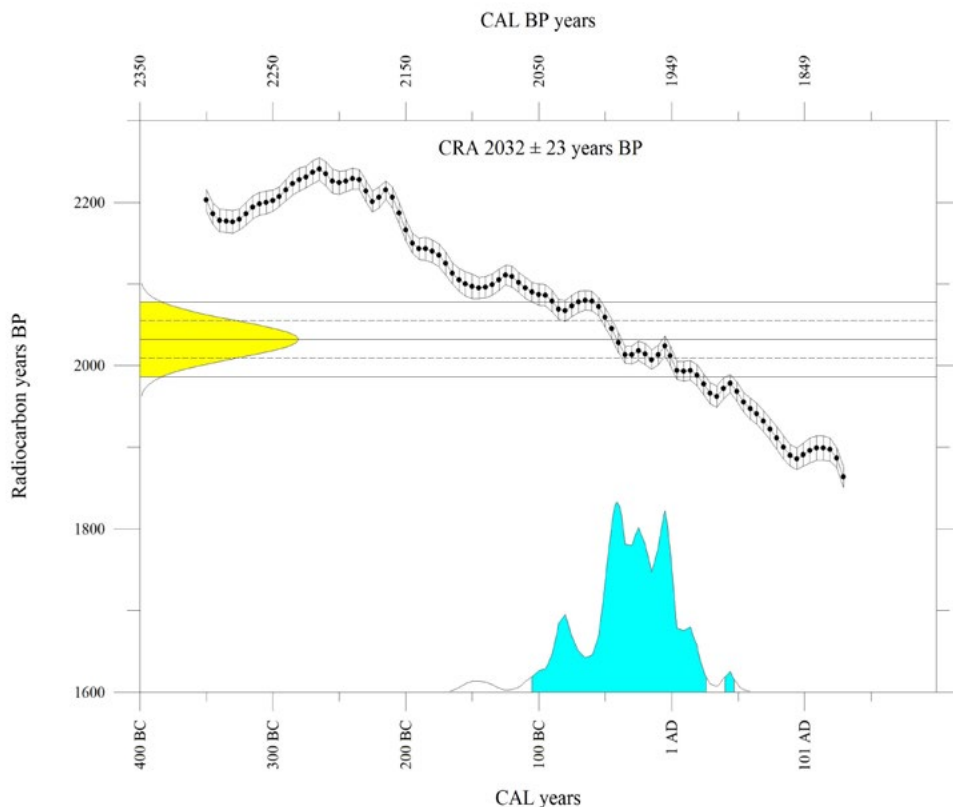
NZA 58693
R 40690/2
Report issued: 7 Apr 2015

CONVENTIONAL RADIOCARBON AGE 2032 ± 23 years BP

Calibrated with IntCal13 (Reimer et al., Radiocarbon 55(4):1869-1887, 2013).

CALIBRATED AGE in terms of confidence intervals

1 sigma interval is 81 BC to 79 BC	2030 BP to 2028 BP (1.2% of area)
53 BC to 5 AD	2002 BP to 1945 BP (67.0% of area)
2 sigma interval is 105 BC to 27 AD	2054 BP to 1923 BP (94.1% of area)
41 AD to 48 AD	1909 BP to 1902 BP (1.0% of area)



Calibration performed using Winscal v. 6.0 adapted from: Stuiver and Reimer (*Radiocarbon* 35(1): 215-230, 1993).

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 PO Box 31-312 Lower Hutt, New Zealand Phone +64 4 570 4644
 Email radiocarbon@gns.cri.nz Website www.RafterRadiocarbon.co.nz

Figure 6.18. Calibration report from radiocarbon analysis of sample T12A (from original wooden storage tray 12A).

Sample T2 as submitted weighed 64.7 mg; after pretreatment 0.8 mg remained, from which 0.4 mg of carbon was obtained. Sample T12A weighed 101.4 mg, of which 5.4 mg remained after pretreatment, from which 0.8 mg of carbon was obtained.

6.6.2. Results

Calibrated ages, at 2σ interval, were as follows:

T2: 52 BCE–54 CE (94.9% of area)

T12A: 105 BCE–27 CE (94.1% of area); 41–48 CE (1.0% of area).

These results are consistent with the likely dates of the auloi that were determined by other methods, and the burial of Queen Amanishakheto falls within that range. The complete calibration reports are shown in figures 6.17–18.

Conventional Radiocarbon Age and $\delta^{14}\text{C}$ were reported as defined by Stuiver and Polach.¹⁵ Fraction modern (F) is the blank-corrected fraction modern normalized to $\delta^{13}\text{C}$ of -25‰ , defined by Donahue, Linick, and Jull.¹⁶ $\delta^{13}\text{C}$ normalization is always performed using $\delta^{13}\text{C}$ measured by AMS, thus accounting for AMS fractionation. Although not used in the ^{14}C age calculations, the environmental $\delta^{13}\text{C}$ measured offline by IRMS is stated where sufficient sample material was available. The reported errors comprise statistical errors in sample and standard determinations, combined in quadrature with a system error based on the analysis of an ongoing series of measurements on an oxalic acid standard.

6.7. Wood Analysis, Caroline Cartwright

Five aulos fragments were submitted for wood identification,¹⁷ which was carried out in two stages. First, two loose fragments of wood from tray 12 A with no identifiable features were provided to the author for analysis. After encouraging results, three more samples were selected from different pipes, from items 025, 063, and 081 (fig. 6.19).

Because of the three-dimensional nature of wood anatomy, each wood sample, irrespective of its size, was fractured manually to show transverse, radial longitudinal and tangential longitudinal sections (TS, RLS, and TLS). Each TS, RLS and TLS wood section was then mounted onto aluminum stubs. Examination of the wood samples and comparative reference specimens (prepared and mounted using the same method) was undertaken in a variable pressure scanning electron microscope (VP SEM), Hitachi S-3700N, using the backscatter electron (BSE) detector at 15 kV, with the SEM chamber partially evacuated (40Pa). Magnifications ranged from $\times 35$ to $\times 550$. The preferred working distance was ca. 14 mm but was raised or lowered as required from 12.6 mm to 16.1 mm. With the BSE detector, 3D mode (rather than Compositional) was preferentially selected to maximize the opportunity to reveal diagnostic features for identification.

6.7.1. Results and Discussion

The VP SEM examination of the five submitted fragments showed sufficient diagnostic cellular features to enable identification as *Olea europaea*, European olive tree wood. This is very interesting as European olive trees are not native to Sudan, although there are African olive tree species, *Olea capensis*, *Olea europaea* subsp. *africana*, and *Olea europaea* subsp. *cuspidata* (syn. *Olea chrysophylla*), which are found in sub-Saharan Africa. However, there are anatomical differences between *Olea europaea*, *Olea europaea* subsp. *africana*, *Olea europaea* subsp. *cuspidata*, and *Olea capensis*, and as the British Museum has comprehensive wood reference material for all these species, it can be confirmed that the fragments are indeed *Olea*

15. Stuiver and Polach 1977. $\delta^{14}\text{C}$ is reported only if the collection date was supplied and is decay-corrected to that date; this was not relevant in this instance.

16. Donahue, Linick, and Jull 1990.

17. Cartwright 2015.



Figure 6.19. Section 025 showing tube and wood associated with the tube.

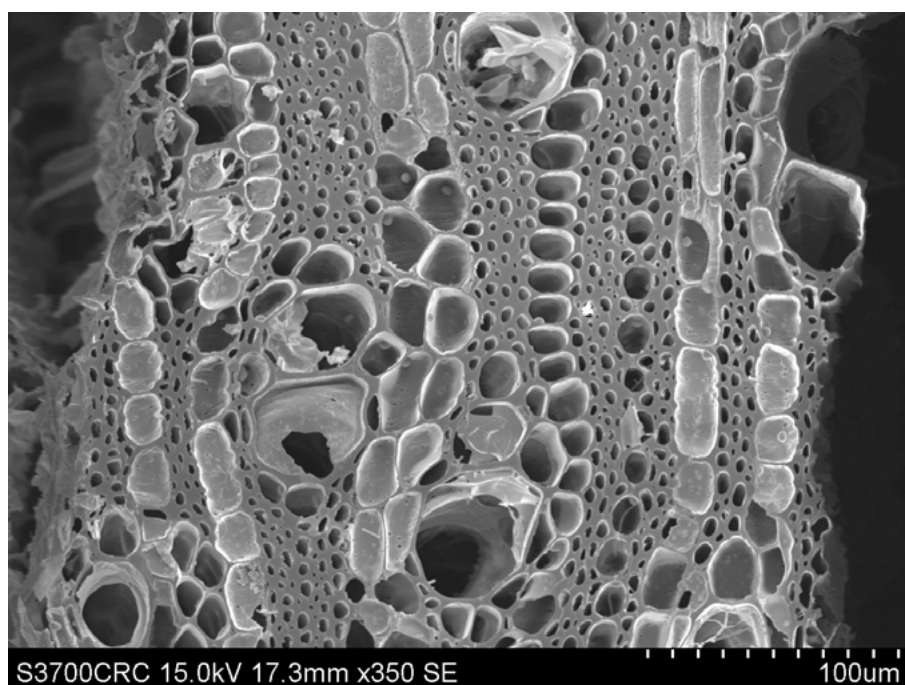


Figure 6.20. A VP SEM image of part of a transverse section of one of the auloi wood samples identified as *Olea europaea*, European olive tree wood. Secondary electron image taken in a scanning electron microscope.

europaea, European olive tree wood (fig. 6.20). Perhaps the items were made in Mediterranean Europe and brought through trade to Meroë.

There are not many published identifications of types of wood used for ancient auloi, but the author has identified the wood from two Classical Greek aulos pipes in the British Museum collections (registration number 1816,0610.502), believed to be from Athens, about fifth–fourth centuries BCE in date.¹⁸ These are *Acer pseudoplatanus*, sycamore maple.

Although the design of an aulos is crucial for determining the quality of the tone and resonance of the instrument, the type of wood selected will also have an effect. It is interesting to consider whether choice of wood is primarily determined by its resonating properties or whether durability is more important.

18. Cartwright 1993.

Olive wood, for example, is hard, strong, close-grained and somewhat oily, with a distinctive decorative grain-pattern and an attractive fragrance. It is easily carved, with a smooth finish. Wind instruments made of olive wood are often said to produce a very open sound. Sycamore maple wood is also easy to carve; it is pale colored, with a fine, even grain, which, when used for wind instruments, produces a soft tone.

6.8. Fiber Analysis, *Joel Stephenson*

Remarkably, despite their age and excavation history, fibers remain present on the upper surface of a number of fragments which are now part of the proposed assemblages numbered 24.3584 and 24.3585 and bone tenons of 24.3586. In the center of the excavation image showing the short pipe fragments (see fig. 4.5) it is possible to see triangular knobs on the top of the pipe; these likely belong to 24.3584.

6.8.1. Fibers on the outer surface (24.3584 and 24.3585)

Fibers found on the upper surface of the pipes appear to wrap around the specific pipe sections with triangular knobs.¹⁹ Yarns can be seen going through the holes in and wrapping around the knobs, indicating that the yarn may have been used to cushion or decorate rotary sleeves during playing. On the bone tenons, in contrast, fibers appear to wrap around them as a sealant for the join between pipe sections. Fibers appear undyed, crystalline, and still well preserved along the top side of the instrument. Fewer fibers are present on sections assigned to the lower half, due to burial conditions.

6.8.2. Images of fragments with fibers (24.3584 and 24.3585)

Within 24.3584, fibers are present on the following fragments: 068–208, 075, 020, 114–004, 062–002 (figs. 6.21–26) while within 24.3585, fibers are only found on adjacent fragments 079–080 and 067 (see the inventory at the end of chapter 5). All fibers are undyed, highly crystalline, with an s-twist and appear to wrap around the rotating sections of the instruments. There are almost no intersecting yarns in the other direction, indicating intentional wrapping more than contact between the pipe and a woven textile fragment.

All five knobs from 24.3584 have fiber wrapped around them and some show fibers going through the hole in the knob and, potentially, following the groove at its top.

Figure 6.26 is a top and side view of a similar knob from fragment 124. Looking at the knob shape without as much corrosion and burial aggregate, it becomes clearer that the knobs were crafted with a relatively large hole and a distinct channel along the top. Reasons for this are not known, but it is interesting to consider that securing a yarn in the groove would make it far easier to wrap each knob, providing either a decorative effect or cushioning for the player's fingers.

6.8.3. Map of Pipe 24.3584

A composite sketch was created to map extant fibers along the reconstructed pipe design of 24.3584 (fig. 6.26). A photograph of each fragment was translated to an outline drawing and the drawings merged in Photoshop to make a sketch combining all respective fragments. On top of this, the approximate fiber remains are shown in red, as they appear along the length of the pipe. The number sequence of pipe 24.3584 is: 116 | 145 | 101 | 062 | 002 | [114–004] | 020 | 075 | 104 | 068+208 | 083 | 140.

6.8.4. Fiber Analysis: Scanning Electron Microscopy

To identify and characterize the fiber found on the surface of the pipe, a sample was taken under the microscope where fibers were removed with pinpoint tweezers and mounted on a glass slide. With polarized light and scanning electron microscopy (SEM), it became clear that the fibers were hollow tubes

19. For filaments recently observed on two pipes in a photograph of instruments excavated from the villa of Fondo Prisco in the Vesuvius region, see Wyslucha and Hagel 2025: 124.



Figure 6.21. Items 068-208 (24.3584). Fibers are present on the knob, on the right. The top view of section 208 shows the wrapping of fibers around the knob.

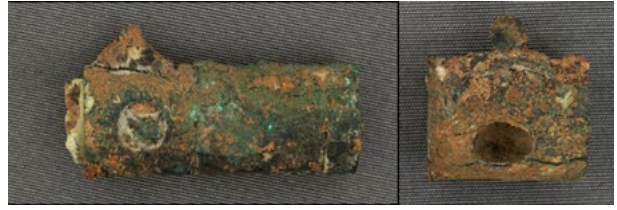


Figure 6.22. Items 075 (24.3584) and 020 (24.3584). Fibers are present on the knobs of both.



Figure 6.23. Items 114-004 (above) and 062-002 (below) both from 24.3584. Fibers are present on the knobs.



Figure 6.24. Items 079-080 (above) and 067 (below) both from 24.3585. Fibers are present on the knob.



Figure 6.25. Knob 124, side and top views, with very little corrosion. This knob's triangular shape is well preserved.

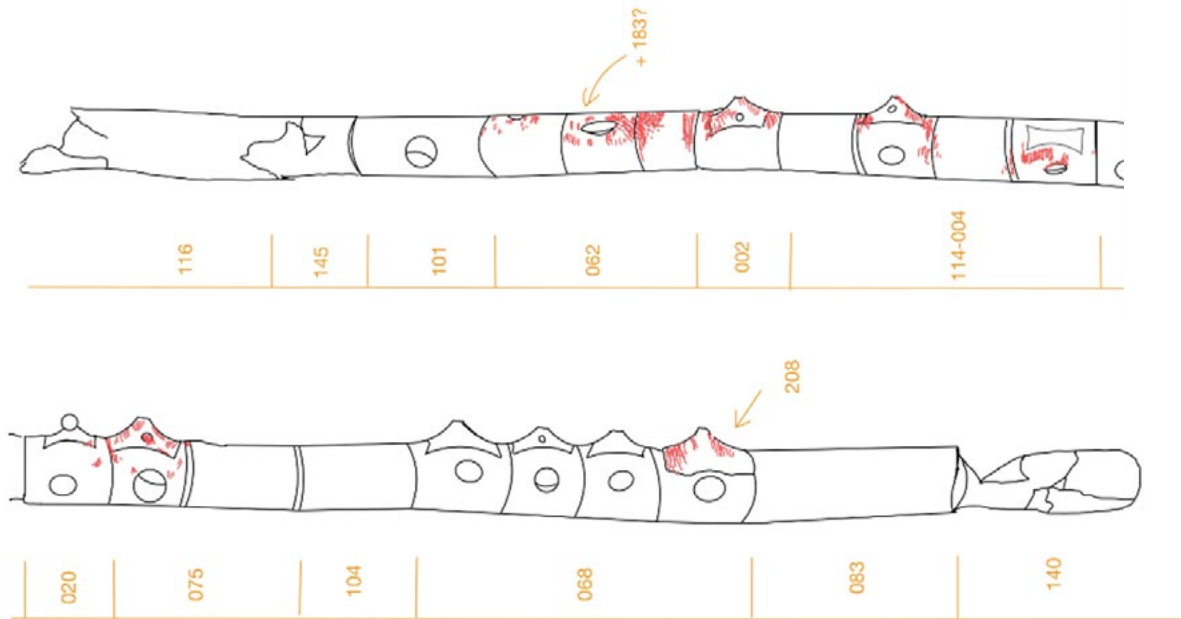


Figure 6.26. Line drawing of the proposed assemblage 24.3584, labeled with item numbers. The red marks indicate the location of fibers.

that have strong cross lines, or nodes, in the horizontal direction. These are characteristics of bast fibers like flax, nettle, hemp, and jute. At breakpoints in growth, nodes form in the horizontal direction, where the fiber becomes more flexible. To identify which kind of bast fiber was found, fiber diameter measurements were taken. The average fiber diameter observed is very small, ranging from 5–15 micrometers with an average diameter of 11.4 micrometers. Small diameter flax is usually only found in areas specializing in flax cultivation.²⁰ For comparison, the average diameter for modern flax fiber typically ranges from 11–16 micrometers. It should be noted, however, that the shrinkage along the width of the fiber, as seen in the SEM images, and dehydration and crystallization of the fibers during burial may influence the measured diameter (fig. 6.27).

The structure of the yarn used to wrap the knobs is visible in figure 6.28. The yarn consists of two single spun threads loosely plied around each other in a counterclockwise direction. This is referred to as the “S” direction because the yarn’s twisted elements wrap so they resemble the letter “S.” The opposite would be a yarn plied in the clockwise, or “Z” direction. To ply a yarn, one must twist in the opposite direction of each single thread, so this yarn would be described as a 2 S plied, Z spun yarn.

In bast fibers processed by manual spinning and splicing, it is also common to find areas on the fiber bundle where the growth nodes of the plant are still aligned as they were originally aligned in the stalk of the plant during growth.²¹ To see if this was also true of the fiber from the auloi, samples of the fiber

20. Vogelsang-Eastwood 1992; Gleba and Harris 2019: 2333; Tata 1986.

21. Rast-Eicher 2005; Leuzinger and Rast-Eicher 2011; Spinazzi-Lucchesi 2018: 15–19.

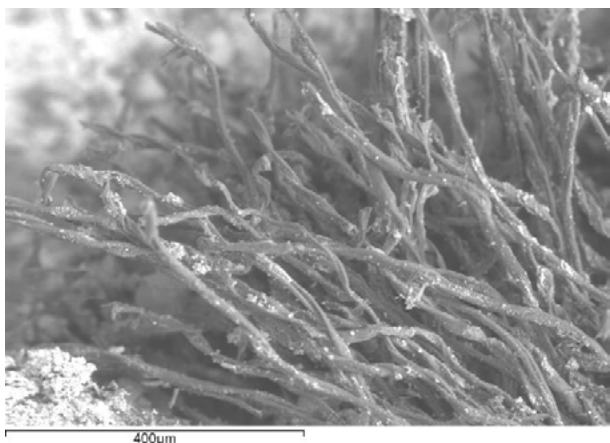


Figure 6.27. Scanning electron image of item 075. Close detail of a yarn end, showing the ribbon-like appearance of bast fibers where the central lumen has collapsed from dehydration and crystallization.



Figure 6.28. Scanning electron microscope image of item 075. This yarn has a 2-ply structure; it is plied in the S direction and spun in the Z direction.

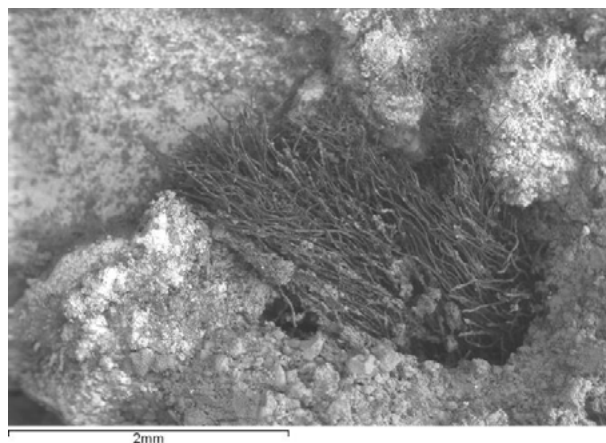
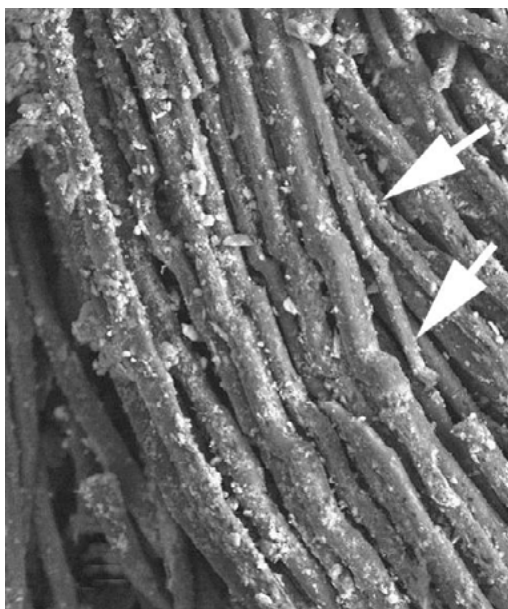


Figure 6.29 (left). Item 075. SEM image showing approximately 150 μ m of fiber. The arrows indicate places where nodes are still arranged in rows as they would have grown on the plant.

Figure 6.30 (above). Image of item 075. Detail of the yarn coming through the hole in the triangular knob.

were examined using a scanning electron microscope (SEM). No distinct splices were found joining fiber to fiber, but in images taken of fiber bundles, alignment of the growth nodes became visible. In figure 6.29, the arrows show areas where the nodes align from fiber to fiber; these areas look like dislocations along the fibers' length.

Figure 6.30 shows fiber coming through the hole in a triangular knob. The end of a yarn splays out of the hole, now surrounded by aggregate. The opposite side of the hole is filled in, trapping this bit of yarn inside. This seems to indicate strongly that the yarn was once threaded through the hole.

6.8.5. Fiber Analysis of Pipes and Knobs: Polarized Light Microscopy

Fiber identification was done using an Olympus BH-2 Polarized Light Microscope in normal light, crossed polars, and with the red tint plate. Images were captured with a tethered Canon EOS digital camera and processed using Adobe Photoshop software. Samples were all prepared in deionized water. All fibers were highly crystalline and almost glassy in appearance, with sharp break edges and a high degree of birefringence, possibly due to mineralization of the fiber in its burial environment.

Fibers were identified immediately as bast fibers due to visible cross-markings and dislocations. Cross-markings are transverse striations that do not change the growth direction of the fiber, whereas dislocations are thicker areas that create a joint-like angle where the fiber changes its growth direction.²² Figure 6.31 shows a fiber from fragment 075 with two very strong nodes and several areas of cross-marking.



Figure 6.31. Single fiber from item 075. Photograph taken through a polarized light microscope at 400X magnification, insertion of a red tint plate showing cross-markings and dislocations present across the fiber that are evidence of the growth of bast plants.

6.8.6. Fibers on Bone Tenons

In addition to yarns seen wrapped over the top side of the instrument, fibers were also found on bone tenons (figs. 6.32–33). These remains appear to form a thin fiber layer, wrapped in a single direction, without twist. They appear to be unspun and wrap around the tenons, potentially to cushion and seal the joins when assembled. In comparison, these fibers are more deteriorated. They are extremely fragile, highly crystalline and have small fiber diameters. The remaining fiber material is flattened and fused to the bone, making it more difficult to sample.



Figure 6.32. Image of bone bulb 064 (from 24.3586), fibers present around the joining item section. Detail of 064 showing the wrapping direction and fineness of the fiber.

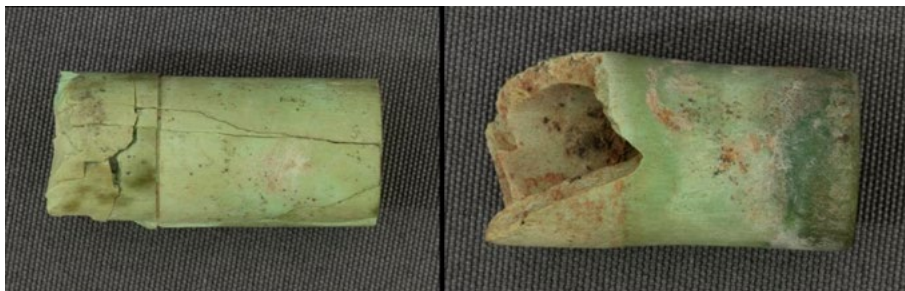


Figure 6.33. Additional bone tubes with fiber present on the tenon.

6.8.7. Fiber Analysis of Bone Tenons: Polarized Light Microscopy

Like fibers seen in figure 6.29, a bundle of fibers from fragment 064 (fig. 6.34) shows alignment with similar dislocations from fiber to fiber horizontally. The fibers exhibit similar fragility, crystallinity, and high

22. Catling and Cayson 1982: 1–4.

birefringence. Figure 6.35 also shows that the fibers on the bone tenons show distinct cross-marking under crossed polars, like the fibers found on surfaces in 24.3584. In this image, the fiber lumen is also visible.

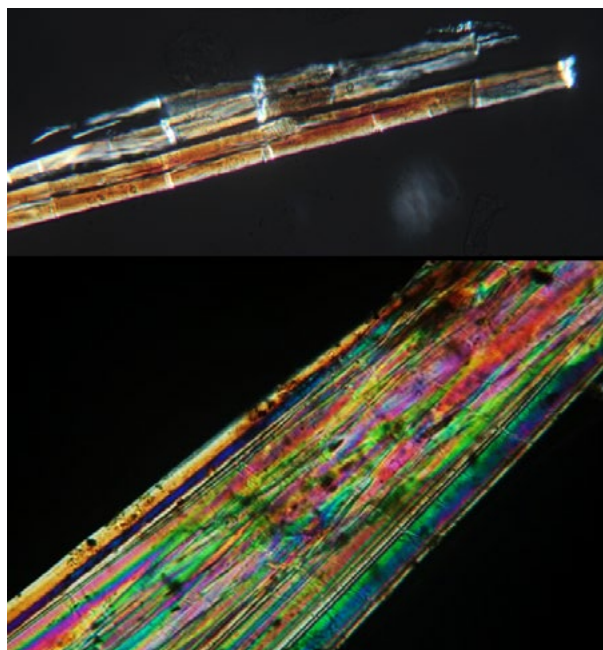


Figure 6.34. Above, fiber from the socket of bone bulb 064, crossed polars, showing cross markings and dislocations. Below, fibers from the same part, crossed polars and red tint plate, it is possible to see the nodes aligned across fibers. Both images at 400X.

6.8.8. Herzog Test: Flax or Hemp

Fibers were investigated using the Herzog method as described by Luniak, Goodway, Haugan, and Holst.²³ To summarize, fibers were taken, prepared in deionized water, and examined with a 40X objective, or 400x magnification, in transmitted light. When possible, a single fiber was brought into focus and the analyzer inserted to view the fiber in crossed polars. The microscope stage was rotated until the fiber was at its most complete extinction position, either parallel or perpendicular to the analyzer. Next a 530-nm full wave compensator, or red tint plate, was inserted 45° to the crossed polars and the fiber color observed. The 530-nm compensator produces either additive or subtractive compensation depending on the crystalline structure and fibrillar orientation and will shift the color of the fiber from black at fully extinct to yellow or blue.

Bast fibers have a cell wall of three microfibrillar layers, which can twist in opposite directions; the middle layer, typically the thickest, has a more dominant influence on twist. The Herzog test measures the birefringence of the light reflected by the microfibrils in the dominant cell wall and therefore is used to demonstrate the tendency of a fiber to twist in the “S” or “Z” direction. Bast fibers that twist in the “S” direction, like flax, nettle and ramie appear blue when the fibers are aligned perpendicular to the compensator and yellow when parallel. Contrarily, bast fibers that twist in the “Z” direction, like hemp, appear blue when aligned parallel to the compensator and yellow when perpendicular.

6.8.9. Results of the Herzog Test

Images of fibers were taken to demonstrate the results of the Herzog test. This test was performed for all samples taken. It should be noted, however, that many of the samples were too much altered, either due to mineralization, crystallization, or dehydration to achieve full extinction. Only fibers that showed clear extinction points were used for identification. Figures 6.35–39 show the results of the Herzog test on fibers from fragments 208, 183, 067, 064, 164.

23. Luniak 1953; Goodway 1987; Bergfjord and Holst 2010; Haugan and Holst 2013.

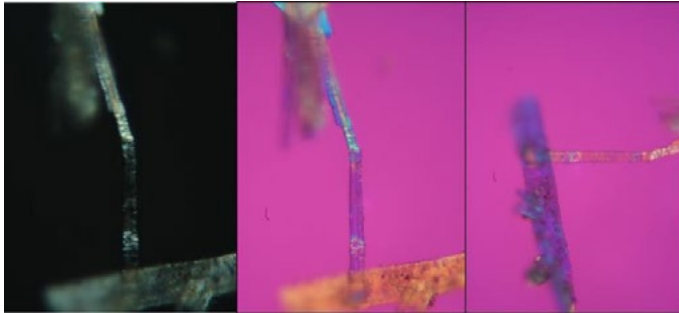


Figure 6.35. Knob 208, hemp. Images of the same fiber with crossed polars and then rotated with the red tint plate to show the shift from blue to yellow as the stage is rotated and the fiber moves from parallel to the compensator to perpendicular.

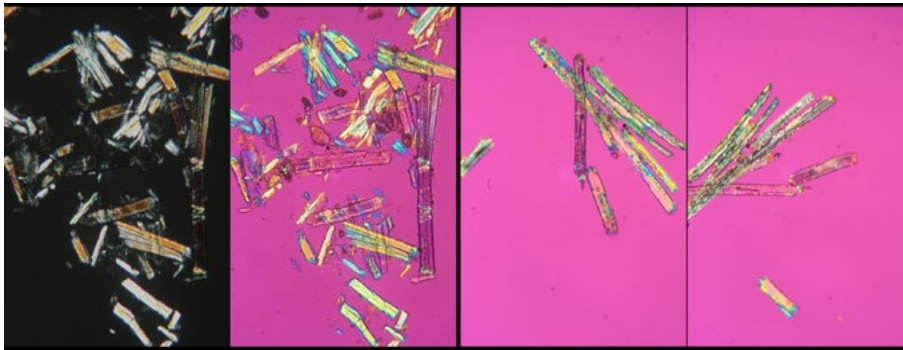


Figure 6.36. Knob 183, hemp. Two different samples showing the Herzog test for hemp.

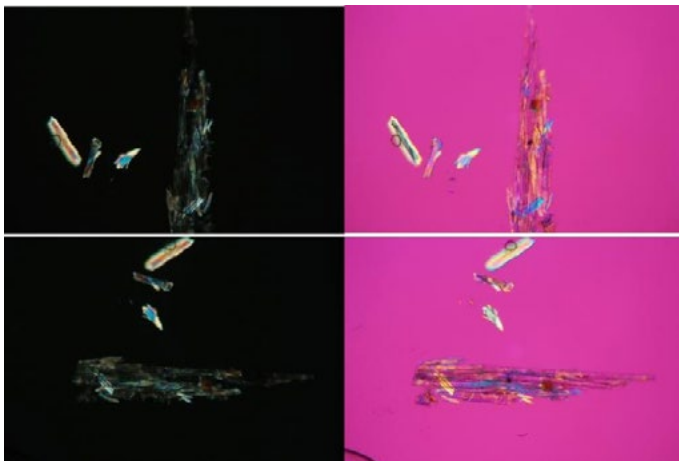


Figure 6.37. Item 067, flax. This test result is more subtle but shows fibers that are more yellow when parallel to the compensator and more blue when perpendicular.



Figure 6.38. Item 064, flax. A single fiber at parallel and perpendicular extinction points, showing yellow when parallel to the compensator and blue when perpendicular.



Figure 6.39. Fiber fragments of bone piece 164, hemp.

Fiber samples from 24.3584 and 24.3585 were identified as hemp. This result aligns with the observation that if the yarns were plied in the “S” direction, they would have twisted in the “Z” direction, as does hemp. The fiber from the bone tenons appears to be either flax or hemp.

The use of both flax and hemp could be one of convenience, since both fibers would have been readily available, or these results may indicate that the pipes originally containing these fragments were made at different times or locations. Although not identified so far, there is also a possibility that flax and hemp were used in combination to increase fiber strength while retaining flexibility.²⁴

Table 3. Summary of the Herzog test results for surface fibers and bone tenons.

Inventory	Identification
208 surface fibers	hemp
183 surface fibers	hemp
067 bone tenon	flax
064 bone tenon	flax
164 bone tenon	hemp

6.8.10. The Possibility of Nettle

Due to the southerly location of Meröe and the trade and cultivation of flax in the area,²⁵ the identification of the “S”-twist auloi fiber as flax seems most likely. However, there have been many recent studies focusing on nettle as a more prevalent fiber in the ancient world than previously thought.²⁶ Because nettle is an “S” twist fiber with morphology that is very similar to flax, the Herzog test and polarized light microscopy show similar results for both. Given the extreme crystallinity, fragility, and mineral contaminants, additional methods of analysis like calcium oxalate crystal identification, or cross-sectional analysis, were not possible. It should be noted that bast fibers can all look remarkable similar microscopically, with overlapping identifying characteristics in fiber diameter, lumen size and shape, birefringence, and with similar appearances in longitudinal samples and cross section. It is difficult to determine the identification of bast fibers from an archeological context with absolute certainty.

6.8.11. Summary of Observations

Through analysis and close visual inspection, it appears that items from 24.3584 and 24.3585 have two “S” ply, “Z” spun hemp fiber wrapped around and through the triangular knobs atop the rotating section of the instrument. In 24.3584, fibers are present on the fragments 068–208, 075, 020, 114–004, and 062–002, while in 24.3585, fibers are only found on fragments 079–080 and 067, which are adjacent in the reconstruction proposed in chapter 7. They seem to be related to rotating sleeves and could explain why the triangular, and also the ring-shaped, knobs are made with a groove along the top. The fibers found appeared crystalline and dehydrated with ribbon-like appearance in the SEM. Fiber diameters were very small, ranging from 5–15 micrometers with an average diameter of 11.4 micrometers, which could be the result of desiccation and mineralization, or the use of very fine young hemp fibers, or both. Polarized light microscopy and the Herzog red-tint-plate test point to hemp as the fiber used on the outer surface of the pipes. These yarns could be either functional or decorative. It would be interesting to compare finds with fibers to look for a pattern that may point to a specific workshop or location of origin.

The bone tenons examined on fragments 064, 067, and 164 have two different fibers, flax and hemp. Again, the fibers are very small, with similar diameters to the hemp analyzed above. They appear to be unplied, in a thin layer, wrapped around the tenons. Now partially fused to the surface of the bone, they

24. Murphy et al. 2011.

25. Thurman and Williams 1979; Yvanez and Woznia 2019.

26. Berfjord, Holst, and Bodil 2010; Holst 2013; Suomela, Vajanto, and Räisänen 2018; Viljanen, Suomela, and Svedström 2022; Frankel et al. 2024.

are extremely fragile when disturbed. These fibers may have been used to insulate the joints for a tight air seal—much like the cork used in modern woodwind instruments. The choice between flax and hemp could be circumstantial—craftspeople using whatever was available for this purpose. Although not observed on this find, flax and hemp fibers were sometimes used together within the same yarn for overall strengthening of the fiber.²⁷ It would be interesting to compare our finds with other fiber finds from auloi in different collections for similarities and differences and perhaps find trends within these selective well-preserved remains.

6.9. Bone Identification: Peptide Mass Fingerprint Analysis (PMF), *Daniel Kirby and Richard Newman*

Peptide mass fingerprint (PMF)²⁸ analysis involves the enzymatic digestion of proteins followed by Matrix Assisted Laser Desorption-Ionization Time of Flight mass spectrometric (MALDI) analysis of the resultant peptide mixture. In the case of leather, parchment, bone and ivory, Type 1 collagen is the major constitutive protein, and for each mammalian source, the amino acid sequence of Type 1 collagen, albeit highly conserved, may have one or more amino acid substitutions. These substitutions change the mass of some peptides observed in the MALDI spectrum, and these masses/ions are used as markers for specific mammalian sources. Marker ions in the MALDI spectra from known reference materials are compared with those from unknown samples for identification.²⁹ PMF can identify mammalian sources to the family level and, in some cases to sub-family and species level. Identifications can be limited by lack of reference samples, although the database is continuously being expanded.

Twelve fragments of (assumed) bone from the auloi were analyzed, using a variety of sample sizes and preparation techniques, as described in detail below. Although samples as old or considerably older than those from the auloi have been successfully analyzed by PMF, most of the analyses carried out on the aulos fragments did not detect collagen, for reasons that are not clearly understood at the moment. Two samples produced definitive results, which clearly indicated mammalian origin from a member of the Bovidae family. Bovids are cloven-hoofed, ruminant mammals that include cattle, yaks, bison, antelopes, sheep and goats.³⁰ There are about 140 extant members of this very large family, and due to lack of detailed databases, individual species often cannot currently be identified by PMF. The maximum concentration of species of bovids in the world occurs in savannas of eastern Africa. Consideration of the dimensions of some of the more intact bone segments of the auloi may help to narrow down possible sources.

6.9.1. Sampling

Initial sampling of some bone fragments involved very small samples that were prepared and analyzed by routine techniques. Given the negative results from the small samples, additional analyses involved larger samples and more complex sample preparation and clean-up techniques.

6.9.2. Analyses

A total of fifteen samples divided into five groups were analyzed. Some samples were analyzed multiple times, using different sample preparation techniques. Positive control mammalian bone samples were included in some of the groups. The groups are discussed separately below. Individual samples within a group were given unique identification numbers. MALDI analysis was performed on either a Bruker UltrafleXtreme MALDI TOF/TOF instrument or a Sciex 5800 TOF/TOF instrument.

27. Murphy et al. 2011.

28. Henzel, Watanabe, and Stults 2003; Kirby et al 2013.

29. Buckley and Collins 2011.

30. “Bovidae,” in online database “animaldiversity.org,” accessed 26 September, 2024.

6.9.2.1. Group 1 (T169)

Samples:

Nine samples.

- a. T-169-A through -F and T169-H were sampled with “sample sticks.” These are polystyrene strips with fiber-optic polishing film attached to two sides. The sticks were rubbed across a small area, entrapping a small amount of material for analysis. After sampling, the film, with entrapped sample was cut off and placed in an Eppendorf tube for analysis.
- b. T-169-G and T-169-I consisted of powdered material that was picked up with a small vinyl eraser cube, which was then placed in an Eppendorf tube for analysis.

All samples were digested and analyzed as follows (Standard Analysis):

1. Samples in Eppendorf tubes with 60 μL 50 mM ammonium bicarbonate (AMBI), heated to 60 C for 1hr.
2. Add 8 μL trypsin at 0.02 $\mu\text{g}/\mu\text{L}$, digest by heating 3hr at 37 C .
3. Combine 3 μL digest solution with 20 μL MALDI matrix solution (40% acetonitrile (ACN) 0.1% trifluoroacetic acid (TFA) saturated α -Cyano-4-hydroxycinnamic acid (CHCA)). Spot onto MALDI sample plate.

Summary of MALDI results:

1. No mammalian collagen was detected in any sample.
2. All samples showed keratin contamination from handling and museum storage.
3. Several samples showed 44 Da “ladders” indicative of synthetic polymer, likely glue that had been used to reassemble some pieces.

6.9.2.2. Group 2 (T173): Increased sample size compared to Group 1

Samples:

Four large pieces of bone.

- T173-E (68 mg)
- T173-F (47 mg)
- T173-G (48 mg)
- T173-H (63 mg).

Modified Standard Analysis:

1. 100 μL 50 mM AMBI, heat to 60 C, 2 hr.
2. 20 μL Trypsin at 0.02 $\mu\text{g}/\mu\text{L}$, heated at 37 C overnight. NOTE: in AMBI: T173-E light yellow, F: light yellow, to orange, G: light yellow, H: Light yellow/orange/red.
3. Combine 3 μL digest supernatant with 20 μL MALDI matrix solution. Spot onto MALDI sample plate. Following digestion, the solid bone samples remaining were stored at -80 C . (See T176)

Summary of MALDI results:

1. No mammalian collagen detected in any sample.
2. No signal above digest background observed in any spectrum. Possible traces of keratin were detected.

6.9.2.3. Group 3 (T176)

Samples: bone remnants from Group 2 (T173) that have been stored at -80 C .

Demineralization of bone samples with HCl followed by digestion:

1. Remaining solids from Group 2: wash 2X w/100 μL H₂O, +200 μL 0.6 N HCl to pellet, demineralize overnight at 4 C.
2. Remove H C l layer, wash pellet with 50 mM AMBI 5X until pH ~8.3. add 100 μL AMBI, heat to 80 C, 3h.
3. Add 10 μL trypsin at 0.02 $\mu\text{g}/\mu\text{L}$, heat to 37 C overnight. The pellet was stored at -80 C .

4. Combine 3 μL digest supernatant with 20 μL MALDI matrix solution. Spot onto MALDI sample plate.

Summary of MALDI results:

1. No mammalian collagen detected in any sample.
2. No signal above digest background observed in any spectrum. Possible traces of keratin/trypsin.

6.9.2.4. Group 4 (T179) (see fig. 6.40)

Samples:

Four mammalian bone controls and two aulos samples:

- T179-A (kudo bone, 54.3 mg)
- T179-B (elk bone, 17.4 mg)
- T179-C (deer antler, 20.0 mg)
- T179-D (eland bone, 78.5 mg)
- T179-E (aulos sample, 86.3 mg)
- T179-F (aulos sample, 33.6 mg)

First method:

Demineralization with HCl, ultrafiltration of supernatant to isolate HCl soluble collagen, then digestion:

1. Add 1 mL 0.6 N HCl to bone samples, incubate at 4 C overnight. Following incubation, samples are cloudy, flocculent.
2. Centrifuge 15 KRPM 10 min and remove supernatant for ultrafiltration.

Ultrafiltration:

3. Apply supernatant to Vivaspin 500 spin filter 500 μL at a time, 12 KRPM 15min. Add remaining supernatant, 15 KRPM 25 min. All samples \sim 100 μL .
4. +500 μL 50 mM AMBI, 15 KRPM 25 min until \sim 100 μL .
5. +500 μL 50 mM AMBI, 15 KRPM until all levels are \sim 200 μL , add 50 mM AMBI as necessary.
6. Vortex spin filter, remove liquid to new 600 μL Eppendorf, Add 10 μL trypsin to samples A-D, and 16 μL trypsin to samples E and F. Digest overnight at 37 C.

Second method:

AMBI solubilization of collagen in the bone pellet remaining from the supernatant ultrafiltration method above.

1. Wash pellet with 50 mM AMBI, centrifuge 15 KRPM. Repeat wash with 500 μL 50 mM AMBI until pH \sim 8.3.

AMBI solubilization:

2. Add 500 μL 50 mM AMBI to neutralized pellet, heat to 75 C, 45 min.
3. Take 60 μL of AMBI supernatant to clean 600 μL Eppendorf tube, add 8 μL trypsin at 0.02 $\mu\text{g}/\mu\text{L}$, heat to 37 C overnight.
4. Balance of supernatant and pellet heated overnight at 60 C. (See T180)
5. All samples from Ultrafiltration and AMBI solubilization: combine 3 μL digest supernatant with 20 μL MALDI matrix solution. Spot onto MALDI sample plate.

Summary of MALDI results (see fig. 6.41):

1. All Ultrafiltration positive control bone samples gave expected mammalian collagen results comparable to sampling of the same bones with sample sticks. For the two aulos Ultrafiltration samples, only trypsin background was detected.
2. All AMBI solubilization positive control bone samples gave expected mammalian collagen results comparable to sampling of the same bones with sample sticks. Both aulos pellet samples showed low levels of mammalian collagen (in addition to tryptic fragments), as shown in figure 6.41, for

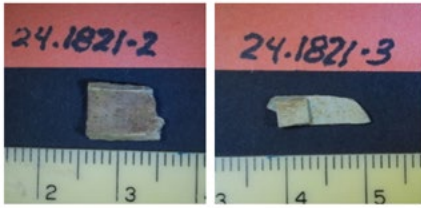


Figure 6.40. Bone sections from which samples T 179-E and 169-F were taken.

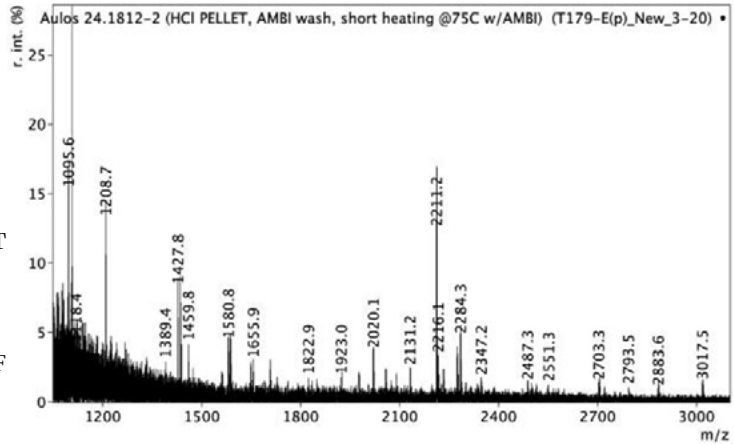


Figure 6.41. Mass spectrum from MALDI-ToF analysis of sample from Group 4.

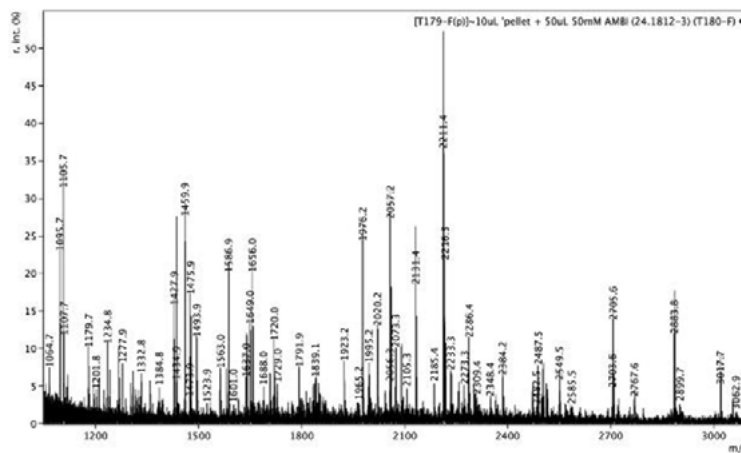


Figure 6.42. Mass spectrum from MALDI-ToF analysis of sample from Group 5.

example, where Ions at 1105 (off scale), 1208, 1427, 1580, 2131 and 2883 Da are significant for identification purposes. Rerunning the MADI spectra of both samples at various sample/matrix ratios produced the best spectra, as shown, for example, in figure 6.42.

6.9.2.5. Group 5 (T180): Extended heating of samples from AMBI solubilization method above to increase solubilization of collagen

Samples: AMBI supernatant and pellet remaining from selected T179 samples (T179-B, elk bone control; T179-E and T179-F, aulos samples) had been heated overnight at 65 C, then stored at -80 C.

Digestion and analysis:

1. Supernatant samples: 60 µL AMBI supernatant, heat to 65 C, 45 min.
2. Pellet samples: 10 µL of pellet “sludge” and 50 µL 50 mM AMBI heat to 65 C, 45 min
3. Add 8 µL trypsin at 0.02 µg/µL, heat to 37 C overnight.
4. Combine 3 µL digest supernatant with 20 µL MALDI matrix solution. Spot onto MALDI sample plate.

Summary of MALDI results:

1. Supernatant samples:
 - T179-B:T180-A (elk bone control): very good spectrum, comparable to sampling of the same bones with sample sticks.
 - T179-E:T180-B (aulos sample): weak: 1105, 1427, 2131, 2883
 - T179-F:T180-C (aulos sample): very weak: 1105, 1427, 2131, 2883

2. Pellet samples:

T179-B:T180-D: very good spectrum, comparable to sampling of the same bone with sample sticks.

T179-E:T180-E: good spectrum. 1105, 1208, 1427, 2131, 2883 markers.

T179-F: very intense spectrum, typical of antelope bone without G marker (fig. 6.43).

The bone is definitely bovid, and it may be possible to narrow down to a family through comparison with published markers and in-house bovid references, although this would require further spectra of better quality.

6.10. Observations on Manufacturing Techniques, *Susanne Gänsicke*

In addition to the different types of material analysis, the aulos sections were examined visually under stereo binocular microscopes at magnifications up to about 50X and a digital microscope.³¹ Specific details of interest included the wall thickness of bronze and bone sections, the fit of inserted tubes (bronze into bronze, bone into bronze, and bone into bone), toolmarks related to manufacture, traces of solder, surface condition, and corrosion.

No solder seams could be detected on the tubes, neither short nor long, by X-radiography, microscopy, or metallographic cross-section of short tube 126. Such seams might have suggested the tubes were formed from rolled sheets of metal. In contrast, solder seams were identified on larger Roman period trumpets of a more complex shape.³² It is therefore suggested that the tubes were formed by initially casting cylinders, which were then thinned and polished by turning.³³ Parallel lines on bronze and silver surfaces serve as evidence of this manufacturing process. An illustration of some of these marks, taken on a tube examined in the SEM, is shown in figure 6.43. The thin silver sleeve decorations on the bone bulbs also show parallel turning marks (fig. 6.44). The silver is too mineralized and fragmentary to determine if it was wrapped as thin silver foil (presumably with a seam) and then burnished by turning, or in some other manner.

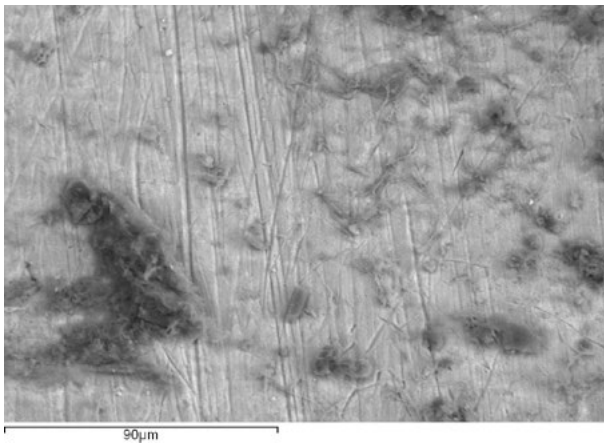


Figure 6.43. Item 070: bronze tube showing parallel lines in the SEM, likely related to turning during manufacture.



Figure 6.44. Turning lines visible in the silver sleeve of bone bulb 111.

31. Hirox CX-5040RZ lens, Luminera Infinity USB 2.0 Camera, Luminera Infinity Analyze software.

32. Mille 2007: 146–55, 267; Pelosi et al. 2016.

33. See also Lawson and Wardle 1988, 1991.

Lathe turning was widely practiced by Roman metal workers. The precision observed on the auloi, however, appears to be more sophisticated when compared to other, likely cast and turned, objects, such as tubes of pumps or cylindrical medical boxes—the latter sometimes display a tight fit between cap and tube, and thin lines at their edges which are reminiscent of the aulos bronze tubes.³⁴ Final turning and smoothing of the surface with a lathe-like instrument would have facilitated the perfect fitting of extremely thin and straight tubes, leaving distinctive parallel marks on the metal surface. These marks can be seen in a few locations on the bronze tubes where these have not been mineralized by corrosion.

Overall, the thinness of the tubes is remarkable, with measurements on bronze tubes not distorted by corrosion being as thin as 0.25 mm. The tight fit between tubes, whether of bronze or of bone, attests to the high precision of the manufacturing process and the tools used (see figs. 6.45 and 6.46).

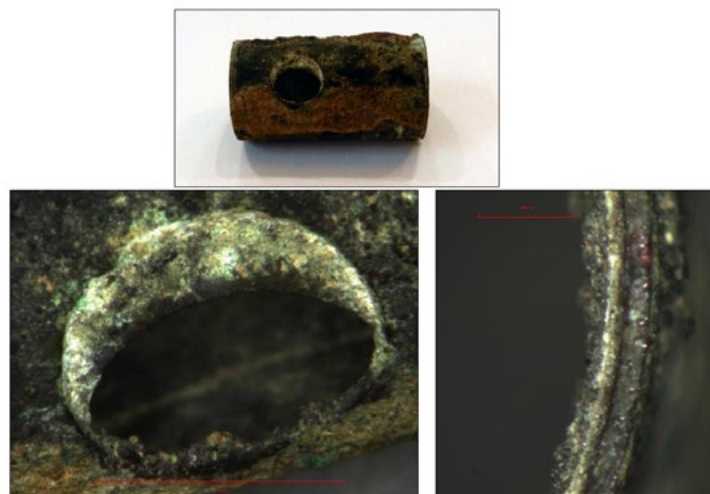


Figure 6.45 The short section 057 consists of two tubes: the inner inserted into the outer. Both have sound holes which are not perfectly aligned, and the overlap appears in the shape of a half-moon. The metal was measured at the open end of the section where both metal tubes are visible.

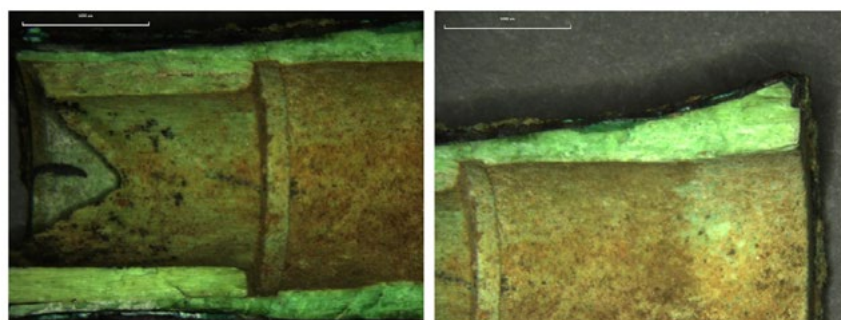


Figure 6.46. Item 160 is one of the best-preserved reed cones, with a very thin outer flaring bone funnel, a cylinder inserted at its thin lower end, and the thin outer bronze wall that wraps over the upper flaring end of the funnel. This cone contained a well-preserved soil “plug.”

Other parts were cast by the lost-wax process: the four sliders with dolphin-shaped end sections, three chimneys which are similar but not identical in make and of different size, and the knobs,

34. For lathe turning and creation of larger tubes, see Mutz 1972; Schioler 1999; for cylindrical medicine boxes see Künzl 2002: 38–42, pl. 39–44; Jackson 2023: 76–77. La Niece and Hook (2023) suggested that the bronze tubes of drug boxes were raised by hammering.

which display a variety of shapes (globular, triangular and ring shaped; see ch. 5). How the thin long sliders, with tiny, notched designs, were cast in one piece is hard to imagine.

As discussed previously, the bronze tube sections were mounted over inner tubes of bone or wood. One unusual long bronze tube (085) displays an inserted short bronze tube with a notch. These two sections may have been joined with solder of unknown composition, although none is visible, and present a singular join of bronze-into-bronze tube within the cache.

Overall, we observe similarities between structural elements, such as the shape of the bone bulbs and reed cones, some of which appear almost identical, even beyond the expected pairing of similar-looking pipes. At the same time, there is a diversity of details, concerning for instance the knobs and the mechanisms. The technical expertise required to shape these items is impressive as is their precision, ingenuity of design, and functionality. The sum of observations raises questions about who fabricated these instruments, how, and where. Might one imagine a workshop specializing in such sophisticated instruments? Was it one artisan or a group? How were the instrument makers trained? Or were the pipes collected over time by a musician from different places? Sadly, little is known about the *chaîne opératoire* that led to their creation. From limited information available in ancient Greek texts and an excavation of two aulos workshops at Delos, a complex picture emerges of instruments made to order, highly priced auloi, and an aulos maker who gathered great riches, as well as evidence of more humble operations.³⁵ Surely in antiquity as today a large variety of needs existed of musicians that ranged from highly trained performers to amateurs. The data provided in this publication will hopefully spur further research into the ancient instrument makers' craft traditions.

The materiality of the Meroë auloi does not reveal the intangible aspects of their lives, their production, nor the rituals they may have experienced, including possible intentional destruction, or the exact sound they emitted. However, interpretations in chapter 7 will reveal more about the type of music that was played and how the pipes may have been used together.

35. Waldemar 1938; Bélis 1998.

7 Reconstruction and Interpretation

Stefan Hagel

The following pages try to condense nine years' worth of ruminations into a coherent argument, as stringent as the evidence allows. Following the methodology briefly adumbrated in chapter 3.2, it will establish the number of the fragmented instruments, classifying them into three general types, not least differentiated by two distinct diameters. Finally, we will embark on reconstructing the details of their original design, assess the pitches they played and interpret these in the context of our knowledge of ancient musical systems.

7.1. The Slender Pipes

7.1.1. General Considerations

The existence of slender pipes without any mechanism is suggested by the presence of at least 24 toneholes without sleeves (or sliders) in slender parts.¹ Of these, two show traces of a (partial) bone core (044, 101), while others still contained fragments of wooden cores. Four of the respective pieces include configurations, especially thumbholes, which clearly assign them to fingered parts (015, 021, 059, 073). Of the rest, up to four might possibly form bass “vent” holes of pipes with mechanisms, whose presence on the topmost parts is evidenced by thumbholes with sleeves, while more than a single bass hole without any mechanism would hardly form a useful configuration on such a pipe. The existence of at least one such “vent” hole is suggested by 044, which has no mechanism but remains of a bone core and cannot therefore have formed part of the simpler pipes, which obviously had wooden cores throughout, and also by 101, within which the transition from a bone to a wooden core had still been preserved.

Consequently, at least $24 - 4 = 20$ holes without sleeves and perhaps up to $24 + 4 = 28$, if we count broken locations that might once have featured a tonehole (018, 035, 120, 132+125), would have formed part of instruments where the top holes had no mechanism. A pipe without any mechanism for any finger would typically have five or six such holes, depending on whether the bass note was sounded from a vent hole or from the exit of the pipe. Therefore, 20 holes are just too many for only three pipes, while four pipes would perfectly accommodate any number between 20 and 24 toneholes. With 25–27, one might equip even five pipes, but these would not pair up to instruments, quite apart from requiring two hypothetical holes in addition to using one on 031, whose wall thickness and corrosion appears to set it apart from the rest of the group. In short, it is practically certain that the parts in question are the remains of four pipes and therefore two instruments. This is corroborated by the mentioned presence of four sections whose fingering would have included the thumb.

Among the slender pieces we also find a significant number of metal tubes one end of which expands to a bell; their rim then bends about 1.5 mm over the end, which not only assured an aesthetically pleasing design but also once helped holding the core in place. Most of these bells are broken, probably because of the thinning the metal had undergone when being hammered into conical shape. They include at least two relatively short parts (116 and 107, possibly also 018, 074, 123), but most notably long cylinders (037, 091, 120, 125[+132], and almost certainly 025), which featured at most one fingerhole (091) or none at all (025, 037). On closer inspection it becomes clear that these “bells” are not all similar. Some of them expand to no more than 18 mm diameter (91, 120), while others are significantly wider, with a peak

1. For the observation of two distinct diameter classes, see chapter 5.2.

diameter of 21 mm (037, 125, almost certainly also 116). The rest has lost their ends. The narrower bells are consistent with evidence for the exit of a particularly slender pipe from Pompeii.²

A number of eight bells would conveniently provide exits for each of the four pipes presently under focus as well as the four slender pipes with mechanism, but it would not be possible to accommodate nine or even ten. Also, it might be difficult to find four pipes out of the eight in question which might plausibly have such long end pieces as the four certain long bells are. The find also appears to have contained just the required number of eight bulbs, even though of one only a very small fragment can be identified; similarly, fragments of the eight once associated fragile reed seats remain.

I have long considered whether two wide “bells” might in fact have formed the upper ends of their pipes, matching the conical reed seats of other instruments, but without a bulb beneath. The existence of such instruments is suggested by some iconography;³ similar bulbless upper ends, though constructed of bone, appear required to make sense of some parts of the aulos find from the Graeco-Bactrian Oxus temple at Takht-i Sangin.⁴ However, the regular metal-encased bone reed seats of the slender pipes themselves are actually not wider than the narrower bells, with maximal diameters of around 18 mm. A reinterpretation of the wide “bells” as reed seats alone would therefore not explain their increased diameters. Instead, one might argue that the difference is related to the material, for instance because encasing a wooden reed seat in bronze required thicker walls; or that a more distinct end was aesthetically preferred in the absence of a bulb. But we seem to have at least three wide bells, not only the two potentially required for alternative reed seats. In addition, if the two were assigned to the upper ends, we would end up with one bulb plus reed seat and one bulb fragment too many, requiring the assumption of an additional instrument, whose body would have been entirely made of wood and would therefore have left no trace. Such an assumption, however, is discouraged by the make of the seven bulbs, which fall in two distinctive categories, one comprising four shorter and the other three longer bulbs. Within these categories, the items are of largely, if not entirely, identical design, give or take a millimeter, just as the pipes to which they must belong fall into two general categories, those with and those without sleeves. If one of the three longer bulbs would have belonged to a wholly different type of instrument, its virtual identity in dimension (and design) with its two companions would be a startling coincidence.

The potentially ambiguous long cylinder, 025, may help deciding the case. In one of the excavation photographs it is found continuing item 113, a conspicuous piece thanks to its unmistakable white accretions, on the one side, while a flaring end that appears to be lost overlaps with it, on the other, which was therefore very probably part of 025 (see fig. 7.25 below). But let us assume, for the sake of the argument, that the “bell” did not originally belong to 025, which would then have been a straight piece of tubing. If it would not form a tail piece, it would have to represent one of the other long sections without tone holes, those bridging the distance between index hole and bulb. In this case, the hole in 113 would become the index hole. Since index holes can be unequivocally identified in three of the fragments in question (015, 059, 073), 113 would need to team up with 021, the only remaining one that provides a thumbhole as required. This joint may not be wholly impossible, although it is not encouraged by corrosion patterns and the material and wall thickness appear different. Adding at least a couple of millimeters at the broken end of 025 plus the typical extension of slender bulbs (42–48 mm) and reed seats (25 mm) as well as a reed of at least 1.5 cm effective length, the index hole would play a note no higher than about 370 Hz, with an interval of a minor third to the thumbhole (290–350 cents,⁵ depending on the orientation of 021. Judging from the relative displacement of the finger holes, the pipe would be left-handed and therefore its counterpart would need to include either 015 or 059, which are designed

2. 18.2 mm on Naples National Archaeological Museum 129589A (Wysłucha and Hagel 2025: 129 fig. 6).

3. See Wysłucha and Hagel 2023: 369.

4. For the Oxus find in general, see Litvinsky 1999, 2010; Lindström et al. 2023; Hagel, Lindström, and Sutkowska 2023; Lindström 2025; Sutkowska 2025; Hagel 2025.

5. Cents are the preferred modern units for expressing interval sizes. A 100¢ make up an (equally tempered) semitone, 1200¢, an octave. Perfect consonances deviate slightly from multiples of 100¢: a fifth has about 702¢; a fourth, 498¢; the difference of 204¢ forms the (whole) tone, the basis of ancient scales.



Figure 7.1: Bulb 134 and the parts of its spigot that had remained in tube 019.



for the right hand. None of these appears to be a good match: the three potential “spacers” above 059, which are 014, 035 (with any restored length), and 133, provide no meaningful musical correlation with any plausible reed configuration. As a consequence, 025 must be regarded as a tail piece whose broken end was once connected to a bell—just as we had already concluded on the basis of the old photograph.

With a number of no fewer than five long slender “bell” sections, these cannot all belong to the four pipes without mechanism. The question of their identity therefore shifts to whether the two with wide ends could have been part of the instruments with mechanism (it would appear preposterous to assume pairings of wide and narrow bells in two different instrument types), on the one hand, and whether a plausible solution with four bulbs can be found for those without mechanism. All this would only be possible if out of 018, 074, and 123, at least two did not originally terminate in a bell—given that 025 must have formed a lower end. One might also surmise that a positive answer to the first question entails that maximally two of the concerned pipes included a bass hole without any mechanism: it would be surprising not to find the notes from the pipe exits used where these were artificially extended by bells of such length if making the bass notes available would only have required one more sleeve in addition to so many others. In other words, a vent hole makes sense relatively close to the exit, where it would ensure a tone quality that resembles that from the other toneholes,⁶ but perhaps not when it is found more than a dozen centimeters above the exit. This may be different on pipes without mechanism, where it may have been customary to plug such vent holes in a different way.⁷

Regarding the top ends of the instruments, the four shorter bulbs differ only by the width of the silver band, which measured 18 mm on 111 and 140, but 16.2 mm on 139; on 134, the band is lost, but differences on the surface indicate that it covered 15.5 mm, and two exposed grooves below align with similar ones on 139 (the region in question is invisible on 111 and 140). The bulb 134 has lost part of its spigot, which remained stuck in 019 (fig. 7.1).⁸ The observed differences of 1.8–2.5 mm in the width of the silver band may not be significant enough to establish two distinct pairs—all the more since 139 and 134, as we shall see, appear to belong to different instruments. If this is correct, all four short bulbs need to be assigned to the pipes with mechanism, leaving the three extant longer ones to those without.

7.1.2. The Slender Pipes with Mechanism

7.1.2.1. Reconstruction

Of the main bodies of the instruments with sleeves, some connections could be established from the in situ photographs. This concerns 062+002+114+004, with one closely and three more widely spaced

6. Compare a vent hole almost on the bell of Naples National Archaeological Museum inv. 129589A (Wysłucha and Hagel 2025).

7. Such a technique needs to be assumed on the wooden Louvre and Berlin auloi (Hagel 2014, 2010) and may already have been used on archaic instruments, judging from the careful choice of their extensions beyond the vent hole (Hagel 2020).

8. In 2023, we retrieved the spigot parts, reassembled them and ascertained that they complete the broken spigot of 134 to the length of the spigots of the similar bulbs.

intervals. If oriented with left-facing knobs (viewed from the player's perspective), their dimensions might yield three tones and a semitone at a particular pitch. Luckily we know enough about ancient tuning standards to assign such a series of intervals at a particular pitch to particular ancient musical keys (*tónoi/trópoi*). In this case, the pitches would correspond to the ancient note signs $\text{O—K—H—}\Gamma/\Delta\text{—A}$ ($f\sharp g\sharp a\sharp c\sharp$)⁹ and belong to Aeolian and Hyperdorian. These scales are however unattested in the extant scores of either the Hellenistic or the Roman period, while the most frequent notes of both periods, the Lydian and Phrygian *mésai* I and M , would fall right between the existing notes, making such an interpretation of the pipe fragment wholly unlikely. Anyway, as we will see below, the other pieces also suggest that the fragments in question belong rather to a knobs-right pipe. As such, it would play Lydian/Phrygian $\text{Y—C/T—P/}\Pi\text{—M—I}$ ($e\flat e f g a$), with slightly raised *parypátai* P (f) and Y ($e\flat$), essentially an inconspicuous scale fragment.

Similarly, 023 and 078 belong together, suggesting a sequence of tone plus semitone with another large step below in a relatively low part of the scale. The holes perfectly fit the notes $\Phi\text{—C—P}$ ($d e f$, once more, Lydian/Phrygian), knobs facing right. Also, 103 and 069 were originally joined, forming a sequence of three semitones optimally fitting O—M—K—I ($f\sharp g g\sharp a$). This part naturally extends the former; unfortunately, the spacer ring that had set them apart appears to be lost. From the excavation photograph, its length can be determined as measuring about 7.2 mm (fig. 7.2).¹⁰

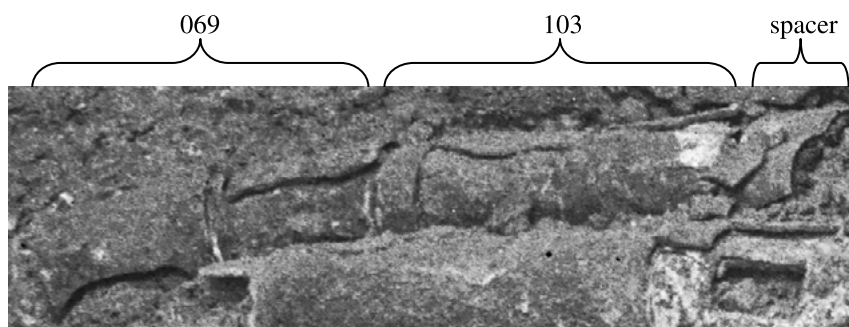


Figure 7.2: 069, 103, and the spacer ring adjacent to 103.

The heart of another pipe is given by compound 079–080–067, a tightly fitting sequence, containing no fewer than six fingerholes. These are obviously spaced by semitones, except the highest two, which are set apart by a larger interval. The dimensions clearly suggest O—M—K—I—Z—E ($f\sharp g g\sharp a b c$), omitting only Θ ($b\flat$) between Z (b) and E (c), a note that is notoriously absent from Roman-period musical scores.¹¹ The knobs face left.

Another large piece is 068 with four closely spaced holes, indicating high pitch. It nicely spans the fourth between Θ (e') and I' (a'), that is, the *hyperboláōn* tetrachord of the natural Lydian key, ending with the note an octave above *mésē*. The hole distances per se do not reflect tones and semitones, the latter being too closely spaced in this high region to be fingered independently. Instead, the fourth is divided into a tone at the upper end ($\text{M}'\text{—I}'$, $g' a'$) and two physical halves of the remainder, apparently reminiscent of the $\frac{3}{4} - \frac{3}{4} - 1$ tone division that had defined the late Classical analysis of physical auletic scales.¹² But what could not be achieved by mere fingerhole spacing is amended by different hole sizes:

9. The notes are transcribed based on the equation of Lydian *mésē* with a , moving from uppercase to lowercase and finally to octave strokes at the boundaries of the “central octave.” The double octave of the diatonic Lydian “Greater Perfect System” is therefore rendered as: $A B C D e f g a b c d e' f' g' a'$ (the “Lesser Perfect System” would in turn include $b\flat$ instead of b). The corresponding pitches are generally about almost a tone higher than modern chamber pitch, with $a' \approx 490$ Hz (see West 1992: 273–76; Hagel 2009a: 68–95). This functional relative transcription must be distinguished from the absolute modern pitches given in a separate row in the diagrams of predicted pitches below; these refer to the common modern standard of $a' = 440$ Hz. In the following, often only the “vocal” note signs are given, which are much more frequent in the extant musical documents.

10. Note that this ring, which already appears exploded on the photograph, cannot therefore have been item 126, which was retrieved intact. Fragment 201, with 8 mm length, appears a bit too long.

11. See Hagel 2009a: 95–96.

12. See West 1992: 97–101; Hagel 2009a: 379–90; 2020: 436–39.

the second from the bottom is noticeably smaller, making the interval below it only a little bit larger than a semitone. By means of cross-fingering—covering the hole below when the upper note of the semitone was played—the size of the semitone could be further reduced, so that the tetrachord becomes an inconspicuous diatonic.

The rest of the pieces, which feature only one or two fingerholes, must be arranged around the established cores following possible physical joints, corrosion patterns and (ancient) musical needs, keeping in mind a consistent orientation of knobs per pipe, the almost certain requirement for at least one thumbhole high up on the instrument, right below a plausible top note, and the constraints of even a trained human hand. In many cases, protruding bone parts restrict the options considerably; in others, perfect fits between the dimensions of the various layers strongly encourage particular joints. An additional, though perhaps not totally reliable guide, are the spacer rings that we often find between adjacent sleeves, and which are frequently preserved at the rims of extant sections: it would normally make little sense to have two spacers next to each other. We might however imagine exceptions to such a rule in case some sections were first assembled from a template, including thin spacers at their ends, to be joined together afterwards. In this later process, custom-made additional rings would have compensated for the inevitable small deviations in part size, ensuring these did not add up to larger errors through the length of the instrument.

Compound 062–002–114–004 and part 068 share not only their knob orientation but are also alike in make and corrosion. It is relatively straightforward to complete the gap between them with the most similar pieces, which also provide important missing notes. Above 004, protruding bone requires a receptacle which is found in 020. This gives the rare Lydian *trítē synēmménōn* Θ (*b_b*), which we have above found missing in compound 079–080–067. Above, 075 provides **Z** (*b*) and **E** (*c*); the extension above the fingerhole for the latter suggests there follows another whole-tone step, omitting **A** (*c*♯). Only one piece and note remains thus to be found between 075 and 068. The evident candidate is 104, being of just the right width and of the same corrosion as well as having a hole in the right place to sound **Ū** (*d*). However, the corrosion pattern appears to demand that this piece is turned around, forming the expected thumbhole.¹³ The regular index hole would thus be the lowest of 068, which plays Lydian *nētē* Θ (*e*). This was the highest note of the standard kithara and was also sounded from the index hole of the higher pipe in the best-studied pair from Pompeii.¹⁴ Since index and thumbhole define the standard upper playing limit, the three even higher fingerholes on 068 are marked as exceeding the standard range—indeed we have seen that they realize what Greek theory termed the *hyperbolaíōn* tetrachord, meaning that of the “excessive” notes.

What about the other pipe with right-facing knobs? Item 048 must belong there because its combination of a thumbhole with two fingerholes defines its orientation. It is a remarkable piece, unique in the Meroë cache, for operating three holes with the same sleeve in a way that all three are opened and closed together. Such a design is hardly useful in the middle of an instrument, where adjacent holes are typically opened alternately to produce different scales, but recommends itself as an upward extension of the instrument’s gamut. At any rate, the three holes are too closely spaced to belong below the established core of 023–078–(204)–103–069. Placed directly above that core, 048 would nicely produce a sequence of a tone and two semitones, establishing the notes **Z—E—A/Δ** (*b c c*♯). This would produce a Lydian chromatic “*pyknón*,” which is not improbable per se, but appears surprising given the fact that the unique sleeve prevents establishing a diatonic alternative. Also, terminating the fingerhole grid at this position would ultimately leave us with unaccounted-for pieces. In addition, the corrosion on item 070 looks tantalizingly similar, and so does that of 057. The former must belong in the upper region because it contains a thumbhole; with rightward knobs, the thumbhole is inevitably the upper one, while the orientation appears defined by the clear-cut corrosion patterns. A thumbhole cannot however be placed

13. The knob position, on the other hand, is unusual for a thumbhole and would appear more regular with the hole facing upside, and the item consequently flipped around. The ensuing pitch difference is small (about 10 cents) and indecisive. The omission of a thumbhole might be explainable if there was no clear preference for a “standard” treble hole among the four or five highest.

14. Hagel 2008, 2012a.

immediately below 048, because this part could not provide a usable index hole above it, given that that hole could only be opened together with the two higher ones. Therefore the only possible arrangement of the three pieces is 070–057–048; the orientation of 057 is established by its knob. This solution also works out musically, and it is bolstered by the fact that both thumbholes are displaced toward the same side, slightly leftwards.¹⁵ Up to the lower thumbhole and the index hole above, which once more define the standard upper range, the Lydian scale is continued by $Z-E-U$ ($b c d$), to a note that we once more find as the treble note of a Pompeian pipe.¹⁶ Opening the holes of 048 extends the same scale by $\Theta-\Lambda-M'$ ($e' f' g'$), just stopping short of its top note, *nētē hyperbolaiōn* $\acute{\iota}$ (a''), which we have found on the previously discussed pipe.

The approach is here very different from the previously established pipe, where individual sleeves and the absence of an additional high thumbhole allow for various combinations and different playing positions of the hand. In the present case, in contrast, the player must take or leave the entire extension at once, trading off modal flexibility for simultaneous access to an additional set of fingerholes.

All other fragments that cannot come from the bass region below the so far established lowest notes of Φ (D) and Υ (e_b) must therefore belong to the remaining two pipes. This regards all items with closely spaced holes, but also the narrow fragments with only a single hole, because placing a needlessly narrow sleeve between two extra-wide ones would only cause disadvantages, as it would increase the hazard of leakage from the narrow sleeves while increasing the friction of the wider. Barring the occasional thumbhole, this rule also sets the orientation of the pieces straight, as long as traces of their knobs can be discerned. The highly problematic item 030 set apart for the moment, which combines unusual green corrosion with a long spigot on one and a sturdy spacer ring on the other end, we are left with 20 fingerholes with sleeves, leading us to expect about ten in each pipe. Six are part of compound 079–080–067, which already betrayed their likely places in the scale. Of the remaining pieces, 210 had largely disintegrated; due to Susanne Gänssicke's efforts, its outer shell has been reestablished to a point where it is possible to obtain its length and the position of its fingerhole; another, smaller, assemblage with a fingerhole may well form the remnants of its internal metal tubing. Two more pieces, 040 and 144, have suffered significant damage, but retained much of their bone cores and parts of the rims of all metal parts. The two fit perfectly together, especially in terms of the boundaries of their external and internal tubing, which are not aligned but shifted by precisely the same amount.¹⁷ Also, the two respective ends would not possibly fit with any other piece. Together they are long enough for a musical evaluation of their four holes, which yields an optimal fit for the row of semitones in the tetrachord above Lydian *hypátē*, $C-P-O-M$ ($e f f\# g$). Another item with similarly shifted tubes is 115, which features two comparatively widely spaced holes. Their distance appears ill-devised for the lower ends, but suggests a whole tone in the upper region. Physically, it would fit very well with 144, but create an interval of almost three quartertones below a whole tone, which would disrupt any scale. It seems we need to posit the loss of a spacer ring of at least 7.2 mm at this position, which appears reasonable enough given the destroyed upper end of 144. With six fingerholes, the scale now includes $\acute{\iota}$ (a) and Z (b).

There remain three items with a single hole (011, 119, 210), one with two (088), and one with three holes (043). The last features a complex combination including a thumbhole, and it requires at least one further hole above it, as we shall presently see. Consequently, the thumbhole of the second pipe needs to be found among the sections with only one hole. Our reconstruction of the two pipes with left-facing knobs have, so far, established thirteen fingerholes for each, from the top down to almost the same note. If the number of fingerholes on the other two pipes was also at least roughly comparable, 043 must have been part of that one whose so far determined portion extends less far upward, since it uses up at least four of the remaining eight holes, its own three plus at least one above it. Since the core starting from 067 will probably need to be extended downward as well in order to match the other pipe, placing 043 above

15. For an extra thumbhole in a single sleeve providing an upward extension of the gamut, see Rome, Museum of Musical Instruments inv. 1015 i.g., the publication of which is in preparation.

16. Naples National Archaeological Museum inv. 76892; see n. 14 above.

17. The full precision of the fit only becomes evident when taking into account that the outer sleeve of 040 has been slightly displaced upward.

it would create a very unbalanced situation, since this pipe would then extend at least five notes beyond Z (b), but the other one merely two or three. So it seems advisable to put 043 above 115 instead, where it adds a row of three semitones, $E—A—U$ ($c \# d$), followed by such a wide rim that the next interval must have been significantly larger than a semitone. Item 119 then, unlike the other two remaining single-hole pieces, might nicely complete the apparently required whole tone step to $n\acute{e}t\bar{e} \ominus$ (e'). If this is correct, a spacer ring of about 3.5 mm must have been lost in between, because the internal metal layer is practically flush on the upper end of 043 but had extended beyond the sleeve of 199 by this amount (in the current state, it does so only by about 1.4 mm because the two layers are now shifted by about 2.1 mm). Several potential spacer ring fragments of 3.3–3.8 mm may serve the purpose; selecting between them would only be possible once it is certain they do not belong on existing pieces.

The last three sections must provide the compound 079–080–067 with a thumbhole, an index hole and probably a downward extension. Item 088, with its two holes on the same side, can only provide for the latter and indeed yields the missing low notes $C—P$ ($e f$), creating two inconspicuous semitones. On the higher end, only 210 establishes a meaningful interval, adding U (d). Section 011, in turn, calls for a spacer ring to become $n\acute{e}t\bar{e} \ominus$ (e'); the required 7 mm are provided by part 126.

As a result, the tonal capabilities of the two pipes with left-facing knobs are very similar. Regarding the tone holes with sleeves, both cover the range from Lydian *hypátē* C to $n\acute{e}t\bar{e} \ominus$ with ten holes. They differ only in a single detail: while one provides a modulating K ($g\#$) between M (g) and I (a), the other inserts an alternative A ($c\#$) between E (c) and U (d).

The details of the latter modulation point are defined by the unusual layout of section 043. A closer look at this fascinating piece will not only allow us better to understand the musical design of the instrument but also to test our conclusions from evidence we have not so far considered in any detail.

7.1.2.2. Understanding Item 043

Above we have stated that 043 has three holes. In a musical sense, this is true: minute differences set aside, it was designed to emit three different pitches. It is also true for the external metal sleeve. Its core, however, features no fewer than five holes, whose azimuths can be roughly obtained by endoscopy and quite accurately by evaluating radiographs (see fig. 7.3). Four of these holes come in pairs that share the same position along the tube, in the center and toward the wider rim respectively, but sit roughly on opposite sides of it. Only the opening at the narrower end corresponds to merely a single hole in the core, which is aligned with two of the other holes. This would obviously indicate the upper side of the section, while the holes on the opposite side must be thumbholes. As a result, the section may be set to three different functional states:

- (0) When the external openings are perpendicular to those in the core, all holes are closed.
- (1) When the hole toward the wider rim is opened as a thumbhole, the central hole is open on the upside, but that at the other end is closed.
- (2) When the hole toward the wider rim is opened as a fingerhole at the upside, the central hole becomes the thumbhole, and that at the other end is also opened.

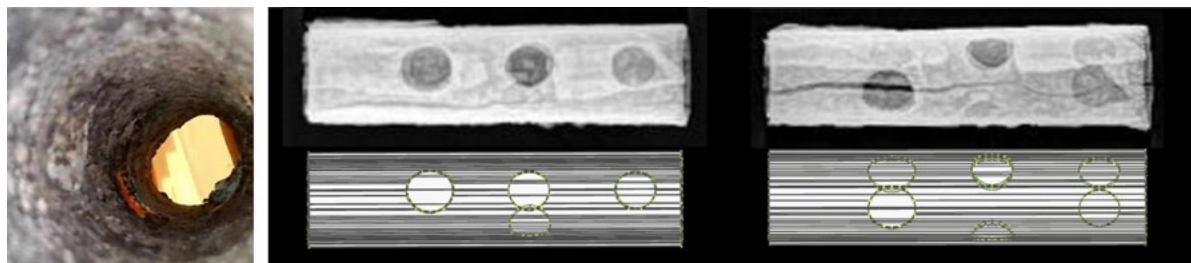


Figure 7.3: Item 043: Left: endoscopic view of the obscured internal tonehole (center left); right: determining the azimuth of that hole using radiographs and 3D modeling.

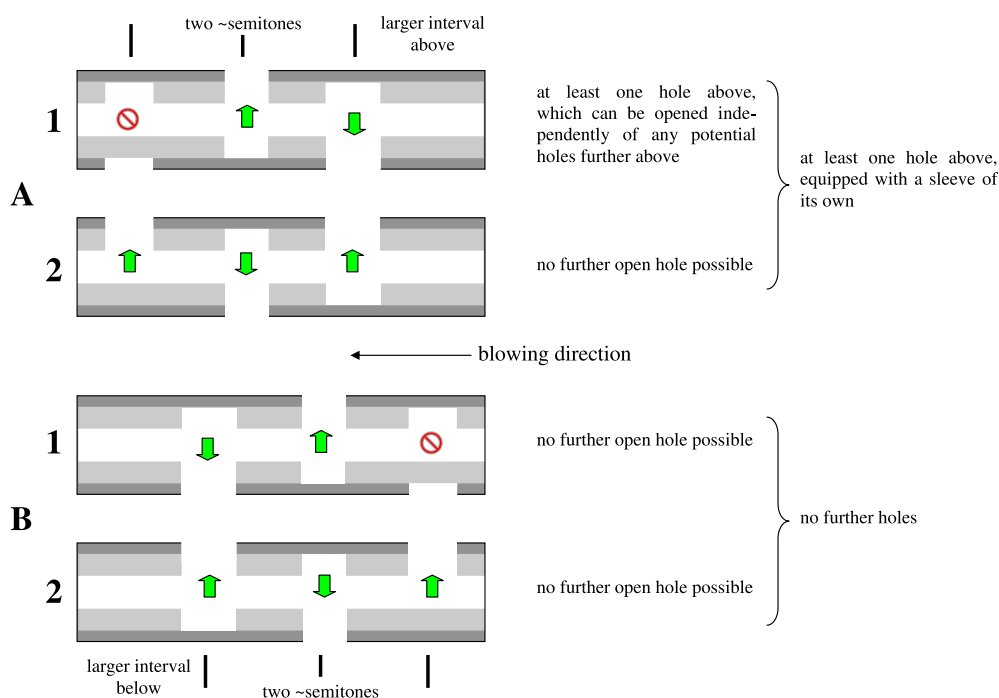


Figure 74: States of 043 in both orientations. Arrows indicate open toneholes (downward: thumbholes; upward: other fingerholes); road-closed signs indicate positions with a closed hole.

The section therefore represents a complex kind of modulating switch. This already suggests that the distances would probably amount to functional semitones. Indeed, the spacing of the holes would exclude playing whole tones on them in any reasonable pitch range.

As shown in figure 7.4, states (1) and (2) entail totally different functionality depending on the orientation of the fragment. When (A) the wider rim is turned toward the mouthpiece, state (1) creates a thumbhole at the upper end, so that we need to expect one more hole above for the index finger. State (2), in contrast, establishes two fingerholes at either end of a thumbhole, which engage index, thumb and middle finger. As a consequence, the index hole required by state (1) needs to be closed by means of its sleeve. With open thumbholes in both states, further holes up the pipe appear very unlikely, but cannot be wholly excluded. At any rate, these would need to be operable independently from the index hole immediately above 043; a sequence such as 043–048 would be impossible.

When (B) the wider rim of the section faces away from the player, either state produces a thumbhole and an index hole; consequently, the section would have to be placed topmost in the fingered range. It may be noted that the thumbhole is always displaced in the direction opposite to the knob (fig. 7.5). Since the sleeve needs to be turned by about 180° between the two states with open holes, the knob may be found on either side of the piece, so that the item defies association based on knob direction.

Orientation B might provide an alternative to the extension of compound 079–080–067 discussed above, producing what we would need to interpret as the Phrygian *nētē diezeugménōn* plus a chromatic “*pyknōn*” above it (Ü—ħ—X, *d eb' e'*). The absence of *trītē* Θ (*bb*) a fourth below ħ (*eb'*), however, makes a Phrygian analysis problematic; anyway, this configuration also fails because the parts it would replace cannot be accommodated otherwise.

We are therefore left with placing 043 on the other pipe, in orientation A, as we have already argued above. Now, however, we are in a position to specify its function with greater precision because in this unique case the design of the instrument not only tells us which notes are in principle available but also which would have been used together. In state (1), part 043 works together with 011 to provide the notes A—Ü—Θ (*c# d e'*). Of these, A does not belong to the natural Lydian key but to Hyperian or any other scale even further removed in the same direction within the circle of fifths.

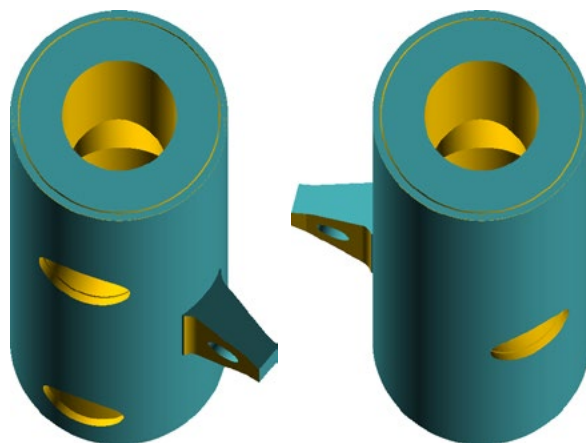


Figure 7.5: Thumbhole and knob positions on 043 in states 1 (left) and 2 (right), viewed in blowing direction A.

In state (2), we get an even more surprising scale fragment, $\mathbf{E}-\mathbf{A}-\mathbf{U}$ ($c\ c\#\ d$), establishing a sequence of three semitones above \mathbf{Z} (b), which cannot all be accommodated within the same ancient *tónos* within a single genus, as far as handbook lore goes: in any diatonic including \mathbf{Z} (b), \mathbf{E} (c) and \mathbf{A} ($c\#$) are mutually exclusive, while the chromatic tetrachord that contains both cannot accommodate \mathbf{U} (d). We will presently return to this topic.

7.1.2.3. Tails and Tops

Before, we need to consider the still missing parts of our four pipes: their vent holes (we have seen there must be at least two), the parts between the highest fingerholes and the mouthpiece, and finally their tail pieces. The last are necessarily the most speculative—where there is a vent hole, the note from the bottom end can only be sounded in the lowest possible fingering position, and the sheer absence of a sleeve on it proves that the note from the pipe exit was of little importance. It follows that we cannot extrapolate the total length of the instrument even tentatively. In contrast, the vent holes themselves need to be integrated within the tonalities of the instruments, and the upper parts must establish plausible lengths, to accommodate a reed of credible size, and second, to allow for near-identical reeds on both pipes of a pair. Finally, we had postponed the discussion of item 030, whose spigot and corrosion type prevented it from finding a place in the upper regions.

With every other sleeve-managed section seemingly in place, the assignment of 030 becomes straightforward. It cannot be placed at the upper end of a pipe with left-facing knobs because its spigot would then interfere with the section below. Nor does it make much sense above 048, which ends with an index-finger hole. It might fit above 068, but would create a minor third, larger than any attested interval between adjacent holes on these pipes, and moreover exceeding the Lydian double-octave as well as any treble notes attested in the musical documents. On top of this, its upper end would come so close to the place where, as we shall see, the bulb must have started that it would inevitably collide with the spigot of the latter. Consequently, 030 belongs in the lower region. There it does not fit on either pipe with left-facing knobs, because these themselves terminate in a spigot that is incompatible with the piece's extant bone core. With a right-facing knob, on the other hand, the spigot of 030 faces upward and cannot therefore dock into 062, where it would obstruct the fingerhole. Item 023, however, provides a perfect home: it terminates in a bone socket, into which the spigot of 030 fits perfectly, butting against the end of the socket precisely when the edges of the metal encasings also touch (fig. 7.6).

The hole of 030 extends the scale by another perfect whole tone down to \mathbf{R} (c). One might still wonder why 030, being the lowest section with a sleeve on its pipe, would end with a kind of spacer ring instead of bordering immediately against the tailpiece. Was an available bell part just too short by a few millimeters? Or, as seems more likely to me, was a sturdy ring with a wall worth of two thin layers technically required for terminating a run of double metal encasings, before the much thinner (and



Figure 7.6: Joining 030 and 023.



Figure 7.7: Item 045, isolated in the excavation photograph.

therefore as light as possible) encasing of the wooden bell core started? On the other pipes, this function would be served by the vent-hole sections, and on the upper end, by the long spacer pieces with thick walls, where, due to the short leverage, weight was of smaller concern than stability.

Above we have mentioned two certain vent-hole pieces, 044 and 101: both contain remnants of their bone cores, while 101 even preserved the wooden socket around a bone spigot. We must expect that the bells were generally formed around wooden cores, just as they are in the finds from Pompeii.¹⁸ A third part, 031, contains no bone but is so similar to 044 in material, wall thickness and corrosion, while differing from all the parts belonging to the instruments without mechanism, that it must be regarded as a third vent-hole section. There probably was no fourth vent hole because item 030 already occupies the region in question on its pipe—only in this case, it seems, was the note from the pipe exit considered a regular member of the instrument's tonality.

The vent-hole sections are easily assigned with regard to the resulting pitches. Items 044 and 031 go below 088 and 040, respectively,¹⁹ supplying the two knobs-left pipes, which have already been proven so similar, with identical bass notes Φ (*D*), reflecting the bass note (“*hyperypátē*” or “*diápeptos*”) of the standard cithara.²⁰ Consequently, the remaining 101 goes below 062, where it happens to provide just the same note.

The tail pieces themselves, as has already been said, necessarily remain a little speculative. We may either imagine that the two pipes of each pair were of the same length, or that both pairs had similar longer and shorter members, or that the lengths were somehow random. Pairs, we must presume, were formed of two pipes with knobs facing in opposite directions. It does not seem that the existing material can be arranged to pairs of equal length, but the assumption of similar inequality may well be borne out. At any rate, a long bell such as 037 can hardly have belonged to the pipe that so far terminates in 030 and is therefore already much longer than the others. Bell 037 may therefore be assigned to either of the knobs-left pipes, which are otherwise of very similar length; from the corrosion, a joint with 031 appears more likely.

The broken bell part 125 probably belonged to the same piece as 132, even though no physical connection can be established: both share an otherwise unique form of yellowish corrosion, preferably splintering along more or less straight lines (fig. 7.8). Attached to 044 and positioned as close to each other as possible, their bell terminates at the same point as its counterpart. Bell 116 might then belong with 101. If spacer ring 145 is added in between, a part that appears similar not only in coloring but also shows a related fracture pattern (fig. 7.9), the pipe end would sound Lydian *hypátē hypatôn* Γ (*B*) a fourth

18. E.g., Naples National Archaeological Museum inv. 129589 (except A).

19. This appears to contradict the evidence presented by Bodley 1946: 234 (plate VI.2.c), where 088 is joined by a “plain sleeve, O.D.-14 mm.; L-49 mm.; finger-hole, partly covered by ivory core of the next tube,” almost completely hidden in the photograph. This must be 045, which not only does match Bodley's length precisely, but is also the only item in the general length range with a single hole sufficiently close to the rim to overlap with the spigot of 088 (the holes in 042, 060, and 081 are too much in the centre). But in the excavation photograph, part 045, unmistakable for a special heart-shaped corrosion mark, is not attached to any other piece (fig. 7.7). At any rate, Bodley's internally “covered” hole is impossible in the first place. Where a spigot reached into the region of a hole, it was of course drilled as well. The conclusion appears inevitable that the compound published by Bodley was only established after the excavation; the same is true for his V.9 (230), see Hagel 2019: 178.

20. West 1992: 221.



Figure 78: Parts 132 and 125.



Figure 79: Parts 116 and 145.

below C (e), which may have been an important traditional auletic bass note.²¹ This would be of lesser importance on this particular pipe with its vent hole, but may have been crucial on its counterpart with sleeves throughout. Unfortunately, this last tailpiece is not recognizably preserved. The sad fragment 123 has the required length, but no discernible remnants of a curvature, and so it may as well have been part of something completely different.

Regarding the upper parts, the pool includes (at least) ten slender sections without toneholes (012, 013, 014, 016, 019, 066, 074, 083, 084, 133), which need to be distributed between the 8 slender pipes. All of them except 074 are sufficiently complete to know their lengths. The corrosion on 019 suggests it continued 048, while the long 066 complements 119 to the same upper length. None is long enough to fill the required space above 011, but a combination of 013 and 016 does nicely, while 083, thanks to being just a little bit shorter than 013, 016, and 019, works above 068. A *syrix* hole close to the rim of 016 matches one in the spigot of bulb 139, which therefore belongs there. On the other hand, as mentioned above, a part of bulb 134 had remained in 019, establishing another connection.

The top pieces, finally, the typical conical parts that received the reed mouthpieces, are mostly fragmented and extremely difficult to assign to particular bulbs; it is not even clear whether they were glued on or could be moved by a small amount in order to fine-tune the pipes against each other, as seems to have been the case on the most famous instruments from Pompeii.²² For the following evaluations one exemplary “reed-seat cone” will be used throughout. Since the two respective parts of the same instrument were certainly of the same length, this cannot negatively impinge on the assessment of any individual instrument; we only need to be cautious when comparing the effective reed lengths between different instruments. We thus obtain pipes of varying lengths, between 53.9 cm and 58.3 cm.²³

7.1.2.4. Pairing

How are the four reconstructed pipes correctly combined to complete instruments? In order to identify them for the moment, we can use the numbers of one important core piece of each: 040 and 067

21. See Hagel 2009a: 343–64.

22. Hagel 2012a.

23. It may be interesting to compare their average length of 56.2cm with the estimate of “not less than 54 cm” for the instrument represented in the hands of the sandstone statue found in the city of Meroë (Dixon and Wachsmann 1964: 124).

for the two longer, 103 and 004 for the shorter pipes. On a cursory glance, 067 appears to fit better with 004, and 040, with 103; but the eye may be deceived by the happenstances of corrosion. The evaluation of potential harmonicities offers a more robust approach, as it is to be expected that the pipes that belonged together would form a greater number of harmonious intervals. This should generally hold true even considering that the two pairs may have been produced according to the same tuning standard and therefore shared many notes. More precisely, the effects of such a common standard might smooth out any differences but can hardly create artificial differences of a kind that would mislead us. Therefore, if we can detect significant divergences at all, we may trust their nature.

Harmonicity is conveniently measured by the number of intervals between the various notes of an instrument that form consonances within a certain error margin. The method has been proven to be very resilient against the precise definition of that margin;²⁴ in the following I will stick to a conventional threshold of 20 cents, the tenth part of a tone. To determine their respective harmonicities, the four possible combinations of the four pipes—always pairing a longer pipe with knobs at the left side with a shorter one with knobs at the right side—are subjected to an automated optimization, in which the combination of reed lengths is determined that bring about a maximum of consonances.

Since the four bulb sections in question are of practically identical length and there can be no doubt that the largely broken conical reed seats attached to these were of the same length at least within a single instrument, we can also compare the effective reed extensions within each hypothetical pair at optimal harmonicity. This may give an additional clue because it is expected that effective reed lengths do not diverge much within a single instrument: while a small effective difference would normally be present between left and right reed mouthpiece if they are made from adjacent pieces of cane, as described by Theophrastus,²⁵ a larger mismatch of effective lengths would inevitably translate to a physical difference in reed length, causing different distances between the lips, which control the blades of the reeds, and the upper ends of the two pipes, invalidating the symmetry of the bulbs.

The figures given in the following derive from optimizing both for intervals between the pipes, which can actually be heard as simultaneous sounds, and those present within each pipe, which can only appear in melodic succession. However, an optimization only for simultaneous concords yields the same result.

Pipe 040 involves the special problem of containing two gaps of undetermined size, as long as the particular spacer rings that had gone there cannot be known. Here the only way forward is to start from gap sizes that optimize the internal harmonicity of the pipe before virtually pairing it with the others. Unfortunately, regarding the lower missing spacer ring, the optimal internal harmonicity of the pipe remains on a similar level across a range from 9 mm to 14 mm, so that similar harmonicity may be achieved within a certain pitch range. Consequently, no single evaluation will suffice. Anyway, the general result is the same for both a narrow and a wide spacer ring, as emerges from a comparison of Table 1 and Table 2, on the one hand, and Table 3 and Table 4, on the other.

In both options, the harmonicity totals fail to turn out sufficiently different to determine the correct pairing. With a narrow spacer ring on Pipe 040, the values are almost identical; with a wide one, the difference still amounts to less than 5 percent. From the criterion of harmonicity alone, the instruments would appear sufficiently similar to be played in both pairings—or at least to have been played together. However, the effective reed extensions beyond the end of the bulb seem decisive. Only when 040 is combined with 103, and 067 with 004, is it possible to use balanced reeds, with calculated 1–4 mm effective differences. Coupling the pipes the other way round, in contrast, results in differences up to 14 mm, large enough to settle the case in favor of the first visual impression. Interestingly, though this may be an accident of burial conditions, all the parts with knobs on which fibers were observed (see ch. 6.8) are thus assigned to the same instrument.

Having identified the likely original pairings, we can now attach less opaque names to the four narrow pipes with mechanism. Classifying them as “Short” in contrast to the much longer instruments to be discussed below, they are conveniently labeled S1 and S2, distinguishing their component pipes as

24. Hagel 2021: 412–15.

25. Theophrastus, *Enquiry into Plants* 4.11.7.

the Lower or Higher one (luckily the treble and bass notes agree in this respect): 040 → S1-L, 103 → S1-H, 067 → S2-L, 004 → S2-H.²⁶ Their estimated total lengths (without reeds) would measure: S1-H: 539.4 mm; S1-L: 581.6 mm; S2-H: 534.4 mm; S2-L: 582.5 mm.

Table 1: Pairings of Pipes 040 (with lower spacer ring of 9.1 mm width), 067, 103, 004: harmonicity (number of unisons, octaves, fifths, fourths, elevenths, and twelfths up to a divergence of 20 cents) and difference in reed length (longer minus shorter pipe). Calculated with: one hole below closed if interval < 3/4 tone, thumbholes closed.

S \ L	between pipes		within long pipe		within short pipe		Total		Reed L-S	
	040	067	040	067	040	067	040	067	040	067
103	42	40	15	11	21	21	78	72	-1.3 mm	-11.1 mm
004	43	40	11	11	15	18	69	69	13.5 mm	3.7 mm

Table 2: Totals of Table 1 for the two pairing options.

	between pipes	within pipes	Total	Reed L-S
040+103 / 067+004	82	65	147	5 mm
040+004 / 067+103	83	58	141	24.6 mm

Table 3: As Table 1, but with a lower spacer ring of 13.1 mm on Pipe 040.²⁷

S \ L	between pipes		within long pipe		within short pipe		Total		Reed L-S	
	040	067	040	067	040	067	040	067	040	067
103	44	40	12	11	21	21	77	72	-2.7 mm	-11.1 mm
004	44	40	14	11	18	18	76	69	13.5 mm	3.7 mm

Table 4: Totals of Table 3 for the two pairing options.

	between pipes	within pipes	Total	Reed L-S
040+103 / 067+004	84	62	146	6.4 mm
040+004 / 067+103	84	64	148	24.6 mm

7.1.2.5. Interpretation

In the course of the preceding arguments, it had already been necessary to refer to ancient note names and notation signs, sometimes in order to assess the plausibility of combinations, sometimes only as a means of describing the respective pitches and setting them in relation to each other. In a way, we have thus anticipated what needs now to be borne out in full argument. Most importantly, where the foregoing has made mention of “fitting” pitches and pitch relations without going into detail, it is now time to supply the relevant data. These will be gained by virtually modeling the musical behavior of the instruments with the help of software I have specifically been designing for the study of ancient doublepipes.²⁸ One crucial tool in this process is the ability to determine the effective lengths of the missing reed mouthpieces that yield maximal “harmonicity,” defined as the greatest number of concords—a process that has formed a reliable foundation for interpreting other, especially many-holed, instruments. We have already used it above for determining the correct pairing of the four pipes. In a second step, the set of pitches obtained

26. These are now assigned the following accession numbers: 24.3582 (S1-H), 24.3583 (S1-L), 24.3584 (S2-H), 24.3585 (S2-L).

27. Part of an apparent spacer ring of 13.1mm length (232), which so far has not found a place anywhere else, is found corroded onto item 085.

28. For details, see most recently Hagel 2021 with references to previous literature. For our purpose, consonances are those that ancient writers acknowledged as such: unisons, octaves, fourths, fifths, and the combination of octaves with any other.

in this way needs to be interpreted in terms of what we know about ancient “scales” from extant literature as well as the surviving melodies and melody fragments, regarding both the sequence of intervals, such as tones and semitones (“*sýstēma*”), and the absolute pitch to which this sequence is set (“*tónos*”) within a well-defined grid.²⁹ Of course, the inevitable precision of the resulting figures is misleading, due to both the nature of the instrument with its flexible reed and the nature of our physical measurements, which cannot reflect the originals in minute detail. Nonetheless, where there are no gross errors in the physical reconstruction, we may expect the results quite adequately to reflect the pitch structures the instruments were intended to play—not least thanks to the experience of the ancient makers who knew how to fine-tune individual holes.

7.1.2.5.1. Instrument S2

Thanks to its better state, without any obvious gaps in the reconstructed tubes, our natural starting point is the instrument we have termed S2, with eleven toneholes on the longer and fourteen on the shorter pipe. As figure 7.10 shows, its optimal reed configuration can be determined unequivocally: there is a single well-defined harmonic peak, which, as we have demanded above, combines two reeds of reasonably similar length.

The resulting pitches and intervals are detailed in figure 7.11. The notes sounded from the pipe exits may be a semitone apart, if the total length of 125+132 on S2-L is correctly estimated from 037 on S1-L. But the actual bass note of both pipes is Φ (*D*), the holes for which are not equipped with rotary sleeves, but already fall within the tailpiece parts of bronze-encased wood. From this common bass note to the highest common note, those that are present on both pipes are: Φ (*D*), \mathbf{C} (*e*), $\mathbf{P}=\mathbf{\Pi}$ (*f*), \mathbf{M} (*g*), \mathbf{I} (*a*), \mathbf{Z} (*b*), $\mathbf{E}=\mathbf{\Gamma}$ (*c*), \mathbf{U} (*d*), $\mathbf{\Theta}$ (*e'*). This is precisely the central octave of the Lydian *tónos* from *hypátē* \mathbf{C} to *nētē* $\mathbf{\Theta}$, augmented at the bottom by *hyperypátē* Φ , and therefore something like a standard gamut in the “natural” key, because the same ninth also formed the typical range of the cithara. The higher pipe complements the upper end of the Lydian scale with the notes $\mathbf{\lambda}$ (*f'*), \mathbf{M}' (*g'*), and \mathbf{I}' (*a'*). This is the so-called tetrachord of “excess notes” (*hyperbolaiōn*), whose nature is indicated by the fact that the thumbhole lies below it, being associated with \mathbf{U} (*d*). In this way, the typical fingering range stops short of the excess notes, the index finger playing *nētē* $\mathbf{\Theta}$ (*e'*). As regards the precise size of the tones and semitones in all the transmitted ancient numeric accounts of the diatonic genus, the instrument comes closest to Ptolemy’s “tense diatonic” (*diatonikón sýntonon*), whose small upper whole-tone intervals combine with adjacent tones and semitones to pure thirds.

In addition to the shared natural scales, we find two “flat” and two “sharp” notes (see also fig. 7.12). The former are $\mathbf{\Theta}$ (*b*) and \mathbf{Y} (*e*), enabling modulation to the two neighboring keys in the circle of fifths (Hypophrygian and Phrygian). The “sharp” notes, in contrast, are \mathbf{O} (*f*♯) and \mathbf{K} (*g*♯), blatantly omitting an instance of *c*♯. In addition to their function in modulating diatonic scales, these notes may also have served in chromatic tetrachords as an alternative to diatonic. In this case, the same pitches

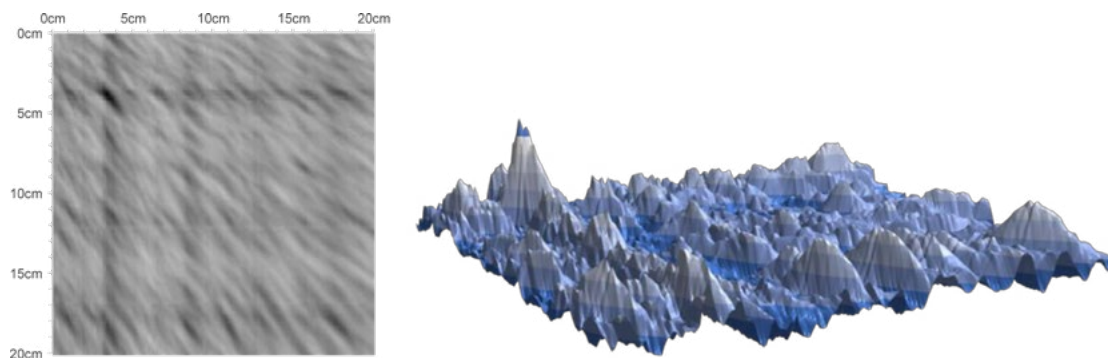


Figure 7.10: Harmonicity of instrument S2, as a color map and an elevation chart within the surveyed 20 cm × 20 cm space. Fingerholes below closed; Gaussian evaluation ($\sigma = 10$ cents). Design: S. Hagel.

29. In the standard theory of ancient harmonics, going back to Aristoxenus, this is ultimately a semitone grid, established by modulating through the circle of fifths. At least one earlier system took a different stance.

would respectively be notated as Π ($f\sharp$) and N ($g\sharp$). This option appears especially attractive in the case of K/N ($g\sharp$): while this note would in principle form part of diatonic Iastian, in the absence of A ($c\sharp$) any actual Iastian melodies would be restricted to the narrow gamut of a fifth. It may however be significant that, in the surviving melodies, N ($g\sharp$) is famously found as a modulating note in an overall Lydian environment.³⁰

Interestingly, the two modulating directions of the “accidentals” are distributed between the pipes, the longer holding the “sharp,” the shorter the “flat” notes.

Finally, there are the bass notes, sounded from the exits of the pipes. The higher one is Γ (B), a pitch that appears to have held special importance in ancient aulos-related music.³¹ It also belongs to the Lydian, while R (C) is omitted. The lower bass note is F (Bb). It is alien to the Lydian key, but may nonetheless have been a traditional element of Lydian instruments. This is suggested, on the one hand, by one of the few extant fragments of instrumental scores, which, while generally revolving around the Lydian, prominently features the note in question (there written as \perp in “instrumental notation”) as the modulating target of a downward run.³² The piece as such cannot be played on the present instrument from Meroë, which lacks the $R=L$ (C).

On the other hand, a similar musical structure, although set to a higher pitch overall, is found on the “Berlin aulos.”³³ It has been argued that the origin of such a kind of apparently modulating bass notes in the tradition of aulos making may have been associated with the practice of extending the gamut of the instrument by overblowing. Since pipes with cylindrical bores, such as all known auloi effectively have, overblow not to the octave like a flute but to the third harmonic and therefore a twelfth, the bass note F (Bb), when overblown, produces a high Π (f') – precisely the Lydian note above Θ (e'), the top note of $S2-L$. To avail oneself of this seamless upward extension of the scale on that pipe, one would however need to close all its toneholes below the five highest, which are fingered. As we have seen, the lowest of them is not equipped with the required sleeve mechanism. In principle, I can see two options to obtain the overblown note nevertheless; but these do not appear equally likely. First, one might of course stop the lowest sidehole by other means, such as a lump of wax or a wooden plug. But then, if the pipe was commonly played in such a manner, why would its makers not simply have added another sleeve? Alternatively, the overblown extra note might only have been accessed when the pipe was used on its own, in the manner of a *mónaulos*.³⁴ Such a practice appears encouraged

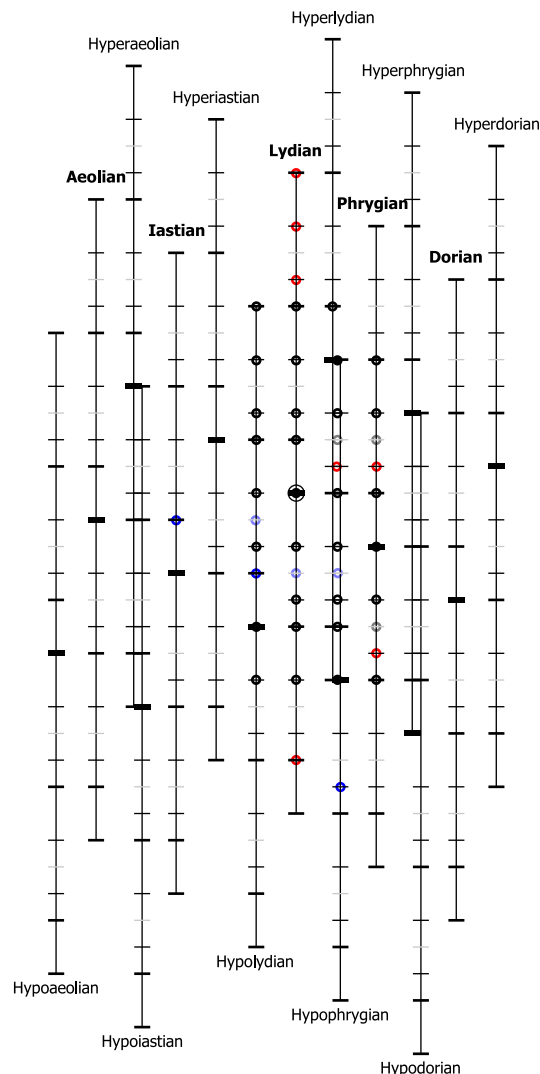


Figure 7.12: The notes of $S2$ in the ancient fifteen-key system (highest notes at top). Blue: only on $S2-L$. Red: only on $S2-H$. Semitransparent: chromatic notes (*chrōmatikaí*). Note signs are given according to the keys in question; in comparison with figure 7.11, $F\perp = \nabla\rightarrow$, $P\cup = \Pi\cup$, $\Theta V = H>$, and $\lambda f = \perp\lambda$.

30. See the invocations, ed. Pöhlmann and West 2001, nos. 24 as well as (not entirely certain) 25.

31. See n. 21 above.

32. Pap. Michigan 1205; see Johnson 2000; Pöhlmann and West 2001; no. 61.

33. Berlin Egyptian Museum inv. 12461/12462; see Hagel 2010; 2009a: 321–23.

34. See West 1992: 92–93. For switching between playing with two and one pipes, see Martial, *Epigrams* 14.63(64): *Saepe duas pariter, saepe monaulon habet*.

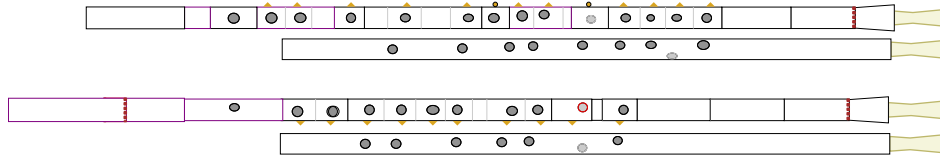


Figure 7.13: Comparing Meroë S2 to the Louvre aulos.

by the number of toneholes in a continuous nonmodulating scale on this pipe. From the lowest to the highest fingerholes, such a scale comprises exactly nine holes, matching five fingers of one hand at the top, where there is also a hole for the thumb, and four of the other hand below, where there is none. In this way, the lowest fingerhole can always be stopped by the little finger. A dual use as aulos component and *mónaulos* may have been especially enticing in Africa, the region that was specifically associated with playing single pipes.³⁵ But this is the only possible “local” trait of the instrument under scrutiny—in all other respects it blends fully in with what we know of ancient Greek music.

What is more, thanks to our increasing knowledge of ancient doublepipes we have become able to draw connections between different finds. Despite their different material, the present instrument bears striking resemblance to the Louvre aulos.³⁶ This wooden instrument of uncertain date but doubtless Egyptian origin plays in the Hypolydian, with a bass note of cithara *hypátē* C (*e*). Just as on S2, its lower pipe reaches up to kithara *nētē* \ominus (*e'*), while the higher includes the *hyperboláiai*, up to I' (*a'*). S2 can therefore be played almost exactly like the Louvre aulos, when the former's row of fingerhole sleeves is set to the Hypolydian scale (fig. 7.13). The only difference is the position of the thumbhole on the higher pipe, which the Louvre aulos has second from the top, while it is found below *nētē* on S2. In spite of a slight divergence in tuning standard, it would actually be possible to play mixed pairings from the two instruments in harmony (figs. 7.14 and 7.15).

Interestingly, the higher Louvre pipe also omits one note from the scale, right above the bass note (the one sounded from the exit). In this way, the total number of its fingerholes is restricted to nine, just as it is on a contiguous scale on S2-L. Here, as well, the most obvious reason for such a design would be an intended dual use as a *mónaulos*. Due to the different lengths of the instruments, the concern about having precisely nine holes necessarily manifested itself on the lower pipe of the Meroë pair, but the higher Louvre pipe. The companion of the latter anyway had no more than seven holes.

No couple of human hands, however, would be able to handle the entire gamut of S2-H. As a consequence, if it was designed for monauletic use as well, its makers would have had to decide on a specific favored range by placing the thumbhole accordingly. Its actual position allows playing the same range as on S2-L, from the bass note up to kithara *nētē* \ominus .

At any rate, there is reason to believe that the blatant musical similarities between the Louvre aulos and S2, two instruments so unequal in make and commercial worth, testify to a widespread instrument design—which is also reflected, although differently, in the Berlin aulos—a design that targeted both auletic and monauletic performances.

7.1.2.5.2. Instrument S1

The other instrument forms a fascinating variation on a related theme. We have seen that the precise evaluation of its intervals is apparently hampered by missing spacer rings between some of the preserved sections. Here a minor part of the “optimization” process becomes a matter of virtual reconstruction. Luckily this affects only matters of fine tuning and the exact pitch standard, within about a third of a tone, not the overall interpretation. In the following I have settled on inserting a 13.1 mm spacer

35. In Plutarch, *Caesar* 52.7, it is expressly mentioned as the instrument of a Libyan virtuoso performer, while in Athenaeus, *Deipnosophists* 174b, Ulpian mocks the Alexandrians for the omnipresence of such an allegedly painful instrument. At least Hellenistic Egyptian *mónauloi* seem to have shared the design of aulos pipes regarding bulbs and conical reed seats, as show small extant wooden examples with two thumbholes (Louvre inv. E11652; E11747, see Ziegler 1979: 94–96).

36. Louvre inv. 10962; see Bélis 1984; Hagel 2004, 2014.

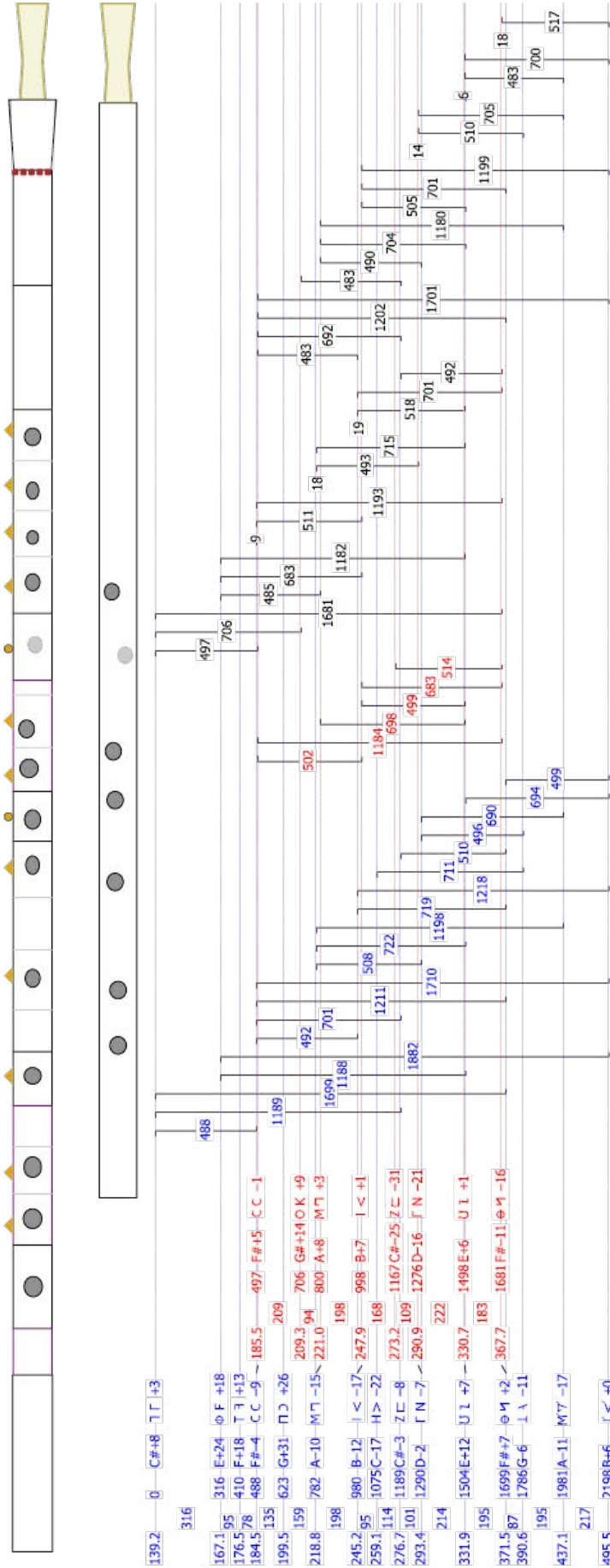


Figure 7.14: Playing Meroë S2-H (reed 35.5 mm) with Louvre 10962-L (reed 36.7 mm). Holes below: closed. Lydian hyperbolaia: 494 Hz (490 Hz + 15 cents); harmonicity: 35/20/6 (threshold 20 cents).

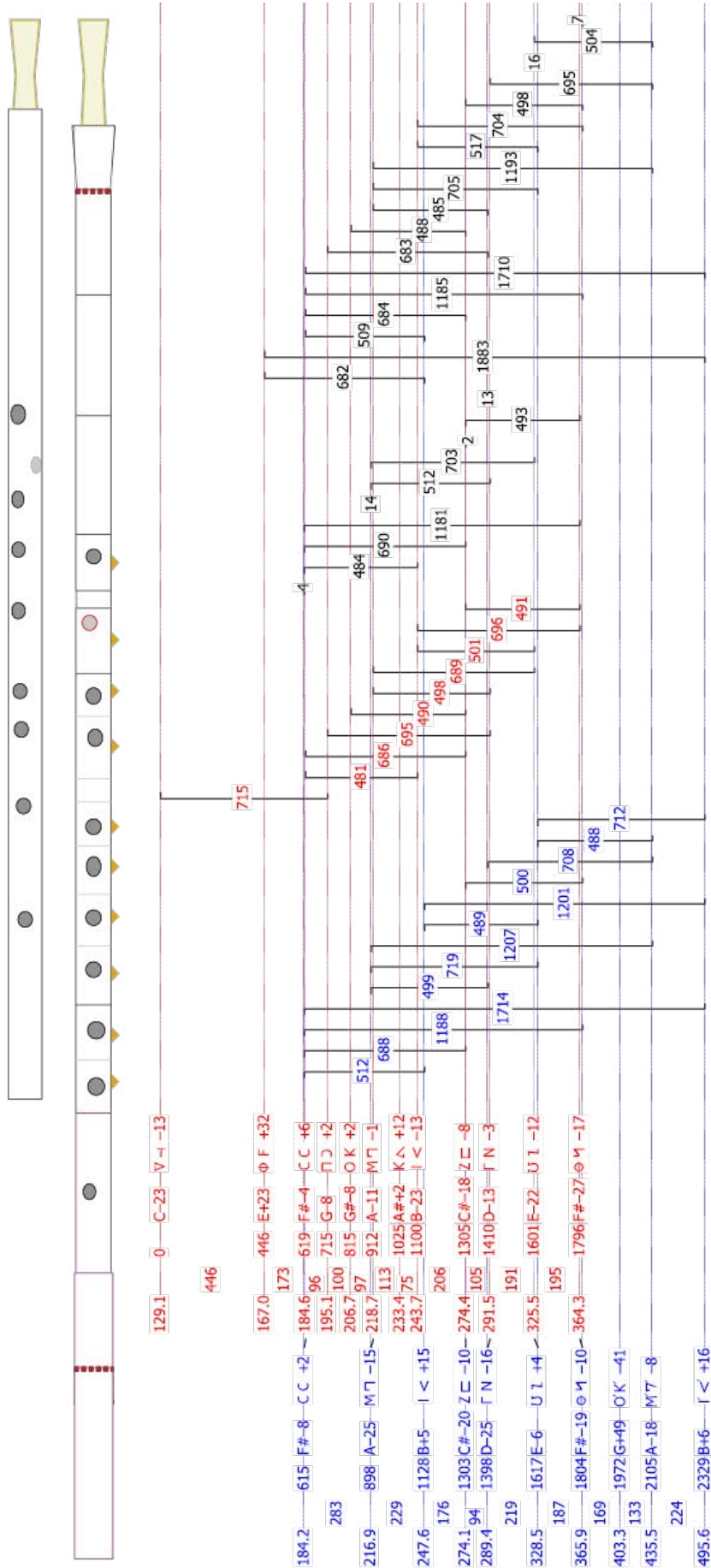


Figure 7.15: Playing Louvre 10962-H (reed 36.3mm) with Meroë S2-L (reed 43.1mm). Holes below: closed. Lydian hyperbolaia: 490 Hz; harmonicity: 28/13/10 (threshold 20 cents).

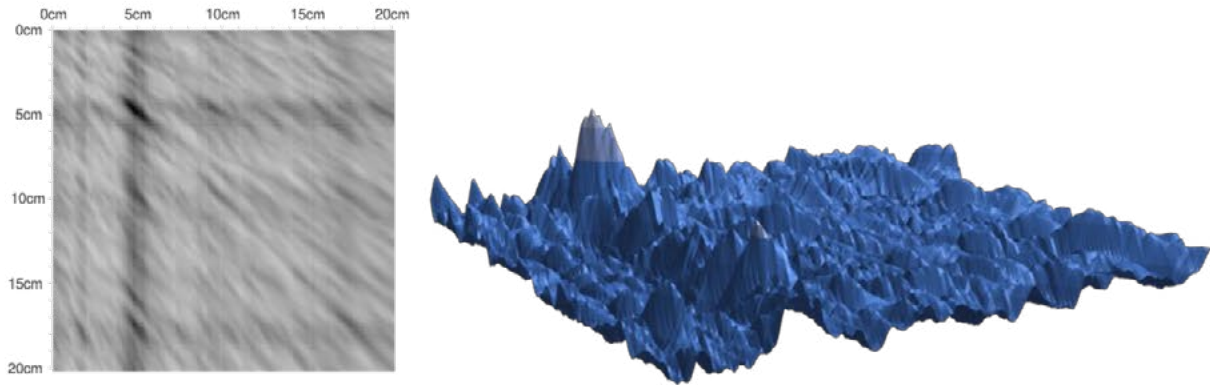


Figure 7.16: Harmonicity of instrument S1 with large spacers, as a color map and an elevation chart within the surveyed 20 cm×20 cm space. Fingerholes below closed; Gaussian evaluation ($\sigma = 10$ cents). Design: S. Hagel.

whose remnants are currently corroded onto 085 below 115; some 3.2 mm, below 119; and finally, a highly hypothetical 3 mm on S1-H between 069 and 070, in spite of the fact that 070 itself is already terminated by a very thin ring and we would not usually expect two spacers side by side. However, the assembling of the tubes as regards section lengths as well as the overlapping of internal encasing and external sleeves appears to have involved more improvisation based on available material than strictly planned engineering, and S1-H has so many more spacers in its well-preserved parts than does S1-L (or either pipe of S2, for that matter) that an additional “license” does not seem extremely unlikely; on the Long Pipes, we definitely find adjacent spacers between 001 and 095 as well as between 071 and 099. One might hypothesize that the makers first assembled part 070 with its small two narrow fixed rings on either side, which prevented its sleeves from shifting, to determine the precise missing spacing only later, after finishing the components of 069. Is it significant that 070 also stands out for its globular knobs (see below)?

Automatic optimization of reed lengths once more yields a single unambiguous peak at almost identical lengths, supporting the general validity of the reconstruction (fig. 7.16). The resulting notes point to a shared pitch standard with S2, about the eighth part of a tone above our reference standard of 490 Hz (fig. 7.17). The pitches that are common to both pipes here also belong to the Lydian scale—but here also to the Hypolydian, because toneholes for O ($f\sharp$) are provided on both pipes.³⁷ The common gamut is the same as on S2, ranging from *hyperypátē* Φ (D) up to *nētē* Θ (e'). The shorter pipe extends the Lydian in both directions. Downward, it adds R (C), which S2 lacks. Conversely, it falls short of S2’s top note, adding merely two notes from the *hyperboláitai*, Λ (f') and M' (g'). In this way, the total range of the two instruments (without the bass notes from the pipe exits) remains identical, but that of S1 is situated one step lower.

Regarding its tuning, the scale conforms most closely not to an especially tense variant of the diatonic, but to the ordinary “Pythagorean,” or better, “pantonic” variant, which maximizes the number of pure fifths and fourths.³⁸ The only noticeable deviation from it is associated with the highest semitone, Λ (f') being 30 cents higher than a pantonic *lémma* would demand. As on the other instrument, this can however be remedied by cross-fingering: the semitone below shrinks to the expected size when the other notes are played in “open fingering,” that is, leaving the hole(s) below their fingerholes open as well, while the middle finger remains on its hole when Λ (f') is sounded from the thumbhole (fig. 7.18).

37. With smaller spacers, optimized reed lengths yield inferior harmonicity tuned up to a quartertone higher—so that one might wonder whether the pitch level might be Phrygian rather than Lydian. But such a hypothesis would be refuted by the fingerhole structure, which would lack harmonically important notes (*paramésē* on S1-L, *nētē* on S1-H, *hypátē* on both).

38. To a certain part, the excellent fit may be caused by the choice of spacer widths and therefore constitute, in principle, circular reasoning. However, since the gaps in question are situated at different positions on the two pipes, all the respective distances are determined on the basis of existing evidence.

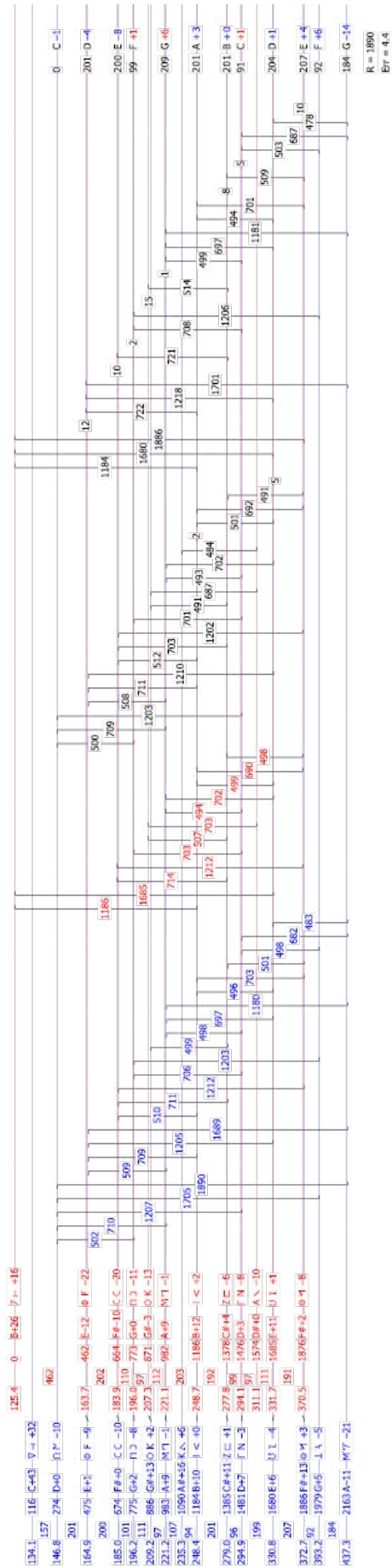


Figure 7.18. Harmonicity of S1-L (reed: 50.6 mm) and S1-H (reed: 50.1 mm). Holes below: one closed if the interval is smaller than three quartertones, thumbholes closed, \ominus closed when playing $\lambda = 1$. Harmonicity: $47/24/12$; ; reference scale: pantonic diatonic

The bass notes themselves seem to lie a semitone lower than on S2. But it needs to be kept in mind that the “bell” piece of S1-H is both incomplete and doubtful, while the original length of that of S2-L must remain undetermined as long as its two halves cannot be connected. At any rate, S1-L reaches down to 7 (A), the lowest note (*proslambanómenos*) of the Lydian double octave, which is optimally suited for supporting the harmonic centrality of kithara *mésē* I (a), an octave above. The higher pipe probably ended a semitone higher at F (B \flat) like S2-L—unless it was perhaps as long as its companion.

Each pipe features two different thumbhole options. In line with its range one tone below that of S2-H, the index hole of S1-H in the standard fingering range played \bar{U} (d) instead of \ominus (e'), so that the thumbhole below falls on *trítē diezeugménōn* E (c). With a single movement, however, the three high holes could be opened, which came with a thumbhole of their own. When the hand moved to this region, the lower thumbhole would either need to be closed by the little finger on the underside of the instrument, which is possible but inconvenient, or by its sleeve, so that the little finger would operate Z (b) instead. The omission of the semitone would create a gapped scale, from the viewpoint of the Greek heptatonic paradigm—or should we rather call it a pentatonic scale, as might make a lot of sense in a region with strong pentatonic traditions up to modern times? After all, ancient Greek music may also have shown vestigial traces of pentatonism. The same *trítē* was reported to have been similarly absent from the Archaic and early Classical lyre, which had covered an octave with only seven strings and therefore lacked one heptatonic degree:³⁹ the present aulos design may thus implement the echoes of long-past musical realities. At any rate, E (c) was still the harmonically weakest note in the tetrachord even in the Roman period,⁴⁰ and therefore the note one might most easily have disposed of, for instance in favor of reaching down to all-important *mésē* I (a) when putting all five fingers on their respective holes.

On the lower pipe, both thumbholes are incorporated in the fascinating section 043, which we have above analyzed in detail. Opening the higher thumbhole creates a diatonic scale, but not in the Lydian key, but in Hyperian or Iastian, which feature A (c \sharp) instead of the Lydian and Hypolydian E (c). It must typically have involved opening the top hole for \ominus (e') as well. Sacrificing the Lydian *diezeugménōn* tetrachord for the Hyperian notes in the same range may have made particular sense in the music of the period: a survey of the notes in the musical documents from the early Roman–Imperial era has shown that this high region of the voice is overwhelmingly found employed in Hyperian (fig. 7.19).

The alternative state of 043, in contrast, rendered the highest fingerhole useless, so that the pipe's scale terminated in E—A— \bar{U} (c c \sharp d). With E (c), these notes must belong in the Lydian/Hypolydian realm, where the pitch of A (c \sharp) was instead notated as Δ . The run of semitones thus offers the alternative

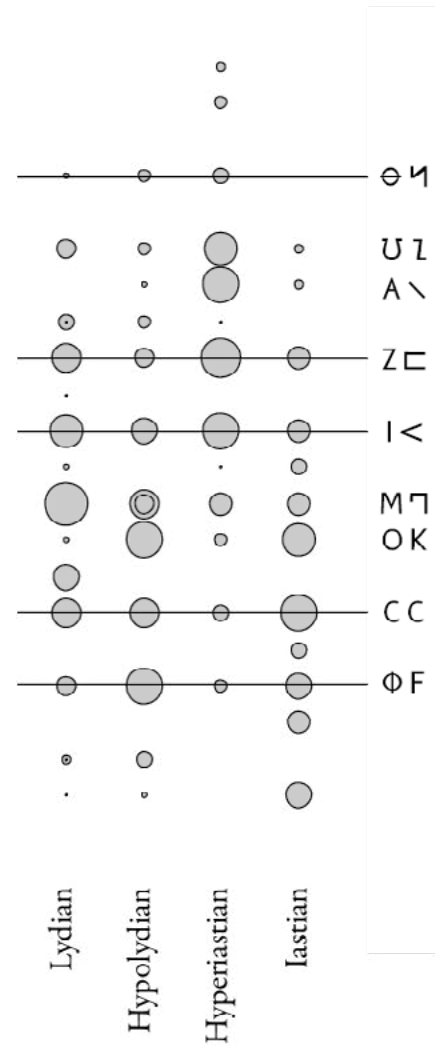


Figure 7.19: Relative frequency of note occurrence in early Roman–Imperial music: documents dated before 150 CE (from Hagel 2009a: 225, diagram 57).

39. The question is discussed in ps.–Aristot. *Problems* 19.32 (differently 47) and Nicomachus, *Enchiridion* 5, who later (9) also quotes the famous passage from the fifth-century BCE philosopher Philolaus (fr. 6) that unmistakably testifies to an octave with gapped upper fourth.

40. For evidence for harmonic hierarchies, see, e.g., Hagel 2022.

between diatonic Z—E—U (*b c d*) and the chromatic “*pyknón*” Z—E—Δ (*b c c#*). Having both chromatic Δ (*c#*) and diatonic U (*d*) available at the same time made modulation “by genus” a design feature of the instrument.

Direct evidence for chromatic is scarce in the Hellenistic period, except in Phrygian melodies, and becomes even scarcer later on. The note Δ in particular is read only five times in the earlier sources, and once on a later papyrus, but hardly anywhere with confidence.⁴¹ However, in this case the documentary evidence must be biased. In reality, the chromatic *pyknón* in question formed part of one of the six kithara tunings (*harmogai*) reported by Claudius Ptolemy.⁴² Otherwise these are diatonic, except for this single tetrachord in the upper range of the Hypolydian; the tuning in question is called *trópoi*. The aulos from Meroë thus establishes a link not only to an almost lost style of music, but also specifically to citharodic performances.

Like all his tunings, Ptolemy describes *trópoi* as an octave scale, an approach inherent to his tabular presentation of tetrachord combinations. On our aulos, however, the chromatic tetrachord lacks its highest note Θ (*e'*), which appears replaced by the alternative diatonic *paranété* U (*d*). In this way, an entirely different octave emerges, ranging from Φ (*D*) to U (*d'*) and terminating at its upper end in a series of three semitones, in an apparent violation of Aristoxenus’s harmonic rules.⁴³ However, the violation is only apparent because Aristoxenian theory would simply explain such a scale as combining pitches that belong to different tetrachords. In the present case, this might entail combining chromatic and diatonic, as we have analyzed it above. Ancient theory, however, would rather have interpreted the note U (*d'*) as belonging to an alternative harmonic path which started a “conjunct” tetrachord directly from *mésē* I (*a*), instead of inserting a “disjunctive” tone first, so that the next tetrachord began only from *paramésē* Z (*b*).⁴⁴ Since both paths were combined in the common two-octave model scale of the “Perfect System,” calling U (*d'*) the “conjunct *nété*” (*nété synēmménōn*) was more economic than resorting to a mixture of genera.⁴⁵ This kind of analysis also allows us to appreciate the function of section 043 more fully: essentially, it allowed switching the top note between two different *nétai* = “top notes,” the disjunct and the conjunct one.

Thanks to the design of part 043, using the conjunct *nété* inevitably entailed also using the chromatic *pyknón* below it. Without mixing genera in the citharodic manner of the *trópoi* tuning, one might correspondingly have set the lower half of the pipe to chromatic as well, resulting in an overall scale of

Φ	C	P	Π	I	Z	E	Δ	U
<i>D</i>	<i>e</i>	<i>f</i>	<i>f#</i>	<i>a</i>	<i>b</i>	<i>c</i>	<i>c#</i>	<i>d</i>

Now this scale is not just a marginal byproduct of remote auletic experimentation. Instead, it resonates with ancient harmonic tradition, sanctioned by associations with “divine Plato” no less than with erudite cosmological lore situated halfway between Pythagoreanizing elitist self-stylization and, as we are now in a position to add, solid musical knowledge. The series of note signs as such is specified by Aristides Quintilianus as a rendition of the ancient Phrygian scale as Plato knew it when composing his *Republic*.⁴⁶ Although Aristides’s work dates only from about 200 CE, it is generally accepted that his ancient scales transmit genuine information, most probably taken from a lost work of Aristoxenus. Aristides, doubtless correctly, understands the notation as enharmonic instead of chromatic, that is, indicating quartertones instead of semitones. But what Aristoxenus considered the proper enharmonic was already in decline in his lifetime. No later than the first century BCE, the same scale had consequently been reinterpreted in terms

41. Pöhlmann and West 2001: Hellenistic: nos. 3.2; 6, fr.28.1; 6, fr.44.2; 16.5 (twice). Roman period: 48.3. In 19.1 it has once been corrected for the stone’s unequivocal A, another time it is more probably part of a word (Hagel 2009a: 280–81).

42. For relating Ptolemy’s mathematical structures and octave-species-based terminology to musical notation and the musical documents, see Hagel 2009a: 56–61, 106–11.

43. Expressed, for instance in Aristoxenus, *Harmonics* 3.74, p. 92.2–3 Da Rios: τρία γὰρ ἀσύνητα ἴσα ἐξῆς ἐν ἀρμονίᾳ μὲν καὶ χρώματι οὐ τίθεται “three similar noncompound intervals are not used in immediate succession in the enharmonic or chromatic.”

44. See Hagel 2000: 46–47.

45. This is how the analogous set of notes in the enharmonic genus is described in a passage quoting Aristoxenus: ps.–Plutarch, *On Music* 1137c.

46. Aristides Quintilianus 1.9, p. 19 Winnington-Ingram, after listing the implied intervals at p. 18.16–18.

of the chromatic, just as we find it crystallized in the design of pipe S1-L. This process may have saved some of the essence of the Classical “Phrygian” as a purely modal scale through the musical innovations of the late Classical and Hellenistic eras, which ultimately obliterated the old modal distinctions to such a degree that scholars have been unable to detect their traces in the scores from the Roman period. In such a new chromatic guise, the structure of the old Phrygian was adopted by Pythagoreanizing philosophers as representing the cosmic harmony.⁴⁷ Its nine notes were attributed to the planetary spheres, starting with the lowest note for the slowly revolving Earth in the center, through the seven planets with increasing pitch—Moon, Mercury, Venus, Sun, Mars, Jupiter, Saturn—up to the sphere of the Fixed Stars sounding in octave harmony with the Earth. It has always been a little surprising why anybody would choose the ethically ambiguous Phrygian for such an undertaking instead of Dorian with its impeccable connotations,⁴⁸ apart from the fact that the Phrygian scale was conveniently contained within the perfect consonance of the octave. Now the emergence of hard archaeological evidence suggests another, purely musical motive: the scale in question was in use and perhaps highly valued.

Its musical appreciation appears supported by its implementation on S1-L not just as a set of toneholes some of which were in practice mutually exclusive, but as available simultaneously in its entirety. On the one hand, the full scale would have been accessible in a monauletic performance on S1-L alone. Notably, the chromatic octave here remains playable despite the physical challenges generally posed by the chromatic genus. These are related to the uneven spacing of the required intervals, which alternate between semitone pairs and minor thirds, with the sporadic major tone in between, while the human hand favors more regular fingerhole distances. Such regular distances had been characteristic of earlier instruments, from the Archaic to the Hellenistic periods, where roughly equal divisions of the fourth were shaped into enharmonic and diatonic tetrachords by partially covering certain holes. Diatonic instruments such as the Louvre aulos, with the occasional semitone between whole tones, also support reasonably comfortable finger spans. In contrast, playing chromatic scales (in the ancient sense of containing chromatic tetrachords) on chromatic instruments (in the modern sense of being based on a semitone grid) involved mastering sequences of three closely spaced holes with larger gaps of whole tones and especially minor thirds in between. The present pipe distributes these optimally. At the top, the four fingers from index to ring finger comfortably manage the three adjacent semitones, while the little finger needs only to reach over to *mésē* | (*a*), a tone apart. When playing the pipe as a *mónaulos*, the problematic interval of a third falls between the hands, the lower hand being responsible merely for the two semitones that form the lower *pyknón*, using index, middle and ring finger. As an extra, the little finger may once more close a hole a whole tone below, so that the ultimate bass note sounds from the exit of the pipe. While this pitch does not technically belong to the “cosmic octave,” it may for instance form the harmonious backdrop for a staccato melody using a closed-fingering technique⁴⁹—a function that the differently pitched bass notes of instrument S2 cannot perform.

While sporadic use of individual pipes as *mónauloi* may appear not unlikely, it was certainly not the rule. Indeed, the entire instrument of S1 is no less intriguingly adapted to expressing the cosmic scale meaningfully, both in musical and astronomical terms, than is its lower component in isolation. S1-H can provide the same pitches as the lower part of S1-L, except the ultimate bass note, which anyway falls outside the planetary scale. Consequently, the hand will play a step higher on S1-H, reaching *mésē* | (*a*) with the index finger. The larger span of a minor third is here unproblematic because it incorporates the position of the thumb, which has no function on the lower part of the pipe. The *mésē* will therefore be available to both hands, which accords with the celebrated harmonic primacy of this note no less than with the unrivaled status of the associated Sun among the planets. When establishing such a “planetary” setup of the instrument, only the lowest note of S1-L remains undefined: any note below *mésē*/Sun

47. Alexander of Ephesus ap. Theon, *Util. Math.*, pp. 138–41 Hiller (see Powell 1925: 129); Censorinus, *De die natali* 13, p. 22, 10–24, 14 Sallmann; Achilles Tatius, *Introduction to Aratus* 17, pp. 24–25 Di Maria; perhaps also ps.-Probus, in *Verg. Georg.* 1.336–337; *Appendix Serviana* 365.6–18. See Jan 1894; Richter 1999; Reinach 1900; Hagel 2000: 46–47; 2005: 84; 2009a: 246 n. 118.

48. The Dorian alternative is actually attested in Pliny, *Natural History* 2.84, and Martianus Capella 2.169–99 (including a small error).

49. For an early hypothesis about closed playing of auloi, see Byrne 2002.

might be used. The harmonically preferable solution would almost certainly involve shutting off all further notes above Φ (*D*), establishing this pitch as a common bass note of both pipes. The harmonic framework would thus be defined by the Earth and the Sun—and the Fixed Stars an octave above the Earth. Also, in the resulting scheme, every note would find at least one concordant counterpart at the interval of a fifth or a fourth on the other pipe. The harmonic superiority of a Phrygian octave, finally, becomes evident by the principal association of *mésē* not with the note a fourth below it, as in Dorian, but a fifth below—replicated an octave higher, a fourth above *mésē*. These three pitches establish the simplest possible structuring of an octave, their frequencies standing in the relation of 2:3:4, adopting the start of the harmonic series and consequently ensuring maximal consonance.

Importantly, this cosmic harmony was implemented as the pipe's primary scale, not just a secondary alternative. As much emerges from the unique functionality of section 043, which forced the instrument makers to encapsulate this important bit of information in its very design. An ordinary sleeve, whether it covers a single hole, as most do, or even three of them like 048 on S1-H, switches between merely the two states of “open” and “closed.” The lever or knob by which the sleeve is operated typically sticks out at a bit more than a right angle from the open hole, in the same general direction for all sleeves in a pipe (or at least all that can possibly be fingered). A modulating sleeve like 043, in contrast, has two different “open” states in addition to the “closed” state, which uncover different sets of holes. As a consequence, the lever will point in different directions in either “open” state; in the case of 043, almost in opposite directions (fig. 7.4). Since all the other levers are placed at the left side of the pipe when their respective holes are open, we must conclude that 043 was in the “normal,” or at least somehow primary, state when its lever pointed left as well. In this state, the pipe is fittingly set to the “natural” scale, including the three semitones at its upper end, and thus to the auletic equivalent of the “cosmic scale.”

7.1.2.6. Knobs, handedness, and playing technique

7.1.2.6.1. Knob shapes

On the slender pipes with mechanism, two kinds of knobs are found by which the rotary sleeves were worked. Most are of triangular shape with a more rectangular base, except five, which are globular and consequently rest on thinner “legs” (see fig. 7.20 as well as figs. 5.9 and 5.11). The distribution of the latter appears to follow certain tendencies, but hardly any discernable fixed rule. They are mounted on parts 020, 048, and 104, as well as on each section of 070.

According to the preceding reconstruction, all these form part of the higher regions of the two higher pipes. Two of them (104 and one on 070) operate a thumbhole, while one belongs to the section with the three highest fingerholes, including a thumbhole (048). Another one gives access to the note Θ/H (*b*).⁵⁰ A similar globular knob is found on a pipe from Pompeii, on the modulating switch between the same note and its “natural” alternative Z (*b*).⁵¹ Marking a (this?) modulating position in such a way may therefore testify to a convention in aulos engineering. Within the “natural” Lydian *tónos*, Θ (*b*) is



Figure 7.20: Typical base shape of a triangular (153) and a globular (127) knob.

50. Note that the tonality of that hole is interpreted wrongly in Hagel 2019, which was based on incomplete evidence.

51. Naples National Archaeological Museum inv. 76893.

trítē synēmménōn, part of the “Lesser Perfect System,” and in a diatonic framework the only note of the tetrachord *synēmménōn* that has no counterpart in the “Greater Perfect System.” Is it significant that the other globular knob on this pipe is connected with \mathbf{U} (*d*), a note that we find referred to as *synēmménē/ōn* (*nētē*),⁵² as if this function was somehow more essential than its role as diatonic *paranētē* in the “Greater Perfect System”? The only two globular knobs on S2-H are thus linked with the only two notes that were designated by their association with the tetrachord *synēmménōn*. Only the lower of the two of course involved actual modulation by “switching” to a note unfamiliar to the “Greater Perfect System.” A broadly similar idea of “switching,” in this case to the *hyperbolaíōn* tetrachord, may have motivated the globular knob on 048. Much more difficult to explain is the lower knob on 070 on S1-H, operating the middle-finger hole that sounds \mathbf{Z} (*b*). Might it have played a role that this was the alternative note to Θ (*b♭*)—compare the modulating sleeve between these two notes on the instrument from Pompeii—even though the latter was not even realized on S1? Was there an ergonomic advantage that we have yet to discover? Or did the makers of this intriguing section just happen to have a couple of globular knobs at hand?

7.1.2.6.2. Handedness and playing technique

A common tenet of aulos lore holds that the longer pipe in a pair is also overall lower, belongs into the left hand and has the holes for the thumb and the index finger displaced slightly to the left, relatively to each other; accordingly, the higher pipe went into the right hand and had rightwards-displaced fingerholes. The rule was established by Stelios Psaroudakēs on the basis of archaic and classical auloi with five or six toneholes per pipe and consequently without any mechanisms,⁵³ but applies to the auloi with sliders from Megara and the Hellenistic instruments from the Oxus temple just as well. As we shall see below, it also holds true for all the Meroë instruments where the respective holes are not equipped with rotary sleeves.

The present set, however, appears to deviate—or, at any rate, instrument S1 does, since the orientation of the thumbholes on S2, which are both found on detached single-hole sections, cannot be ascertained. On S1, in contrast, three extant sections preserve thumbholes together with at least one adjacent hole. The two thumbholes on its shorter, higher pipe, found in parts 070 and 048, thus emerge displaced to the left, contrary to what we would expect from the general rule. On the longer, lower pipe, the complex section 043 provides two alternate thumbholes, displaced to opposite sides. The displacement is always opposite to the respective position of the section’s knob, which is turned either left or right to open either thumbhole (see fig. 7.4 above). In what we have argued is the primary setting, when the knob is aligned with all the other knobs on the pipe, the thumbhole is found displaced toward the right, again in violation of the rule. But it may be rather the type than the particular instrument that stands out. If the proposed pairing of the “Silver Pipes” from Pompeii—so far the only instrument with sleeves that has been extensively published—is correct, we find precisely the same kind of “violation” on these.⁵⁴

In principle, there are two ways to account for this striking design difference. Either we uphold the association of hole displacement and hand—after all, a hard ergonomic argument might outweigh mere cultural conventions—which leads to switching the pipes between the hands, so that the lower goes into the right. Or we maintain the traditional link between hands and relative pitch—after all, cultural conventions are notoriously stubborn—and accept a development in thumbhole ergonomics.

The problem may at first appear a bit academic, but it actually touches upon what may easily be the most vexing question of Roman-period aulos studies: what was the precise purpose of the rotary sleeves? Were they merely used for presetting the available notes before a performance or changing them during breaks between pieces or parts? Or were they actually operated during a performance, possibly without interrupting the flow of sound at all? In the first case, it would make sense to get the knobs out

52. Aristoxenus at ps.-Plutarch, *On Music* 1137c; Alexander of Ephesus at Theon of Smyrna, *Util. math.* p. 140 Hiller.

53. See, e.g., Psaroudakēs 2008: 202; he does not discuss index holes, though, as these would form part of the set against which to judge the thumbhole orientation. Perhaps we should optimally contrast the other holes with that of the middle finger, as this finger is both central, thus closest to a right angle to the pipe, and the longest and therefore expected to reach out furthest compared to the other fingers.

54. Unfortunately, the hole azimuths have not found their way into those publications. On inv. 76893, the higher member of the pair, the thumbhole sits about 170° to the left of the index hole; on 76892, the lower pipe, about 160° to the right.

of the way of the performer's fingers, positioning them so that they pointed away from the hands and therefore "inside." Such an arrangement would be impossible in the second case. Here, instead, the knobs would have to point "outside," toward the hands, where the finger tips could readily push them upward and downward. On our instruments as well as the presumed pair from Pompeii, the "playable" option would retain the traditional scheme of a low left and a high right pipe, while inverting the thumbhole displacement.

Lacking explicit information from ancient texts,⁵⁵ a possible answer rests on two further problems. First, were ancient craftsmen capable of controlling the cylindricity and diameters of the parts precisely enough to allow for airtight rotation at sufficiently low friction to operate the sleeves with a fingertip? Second, if they were, would such a playing technique even be feasible? After many years of experimenting with various sleeve-equipped aulos models, I feel confident to answer the latter question in the affirmative. A confident positive answer to the former is impossible as long as we do not find an aulos in pristine condition, but since the overall workmanship of the instruments is so astounding in many still observable respects, such as the perfectly symmetrical minute raised edges of the sleeves or the incredibly thin bone sockets in the reed cones, I doubt the ancients would have fallen short in this respect.

For the time being, a final decision may be out of reach. Nonetheless I think the balance currently tilts in the favor of "playable" sleeves, not only because these would considerably enrich the art of the aulos. While possible reasons for changing the typical distribution of lower and higher pipes between the player's hands in the course of a continuous tradition bolstered by games and theatres seem hard to come by, there may be a perfect motivation for shifting the thumbholes inwards. The ancient instruments that gave rise to the old "rule" typically demand considerable finger spans. As a consequence, they can only be played by resting the pipes on the thumbs while covering at least the index and middle-finger holes not with the tips, but the fleshy parts of the fingers. A displacement of the upper-side holes toward the hand greatly facilitates this, and the more so, the more widely spaced the holes are. However, once all fingerholes became equipped with rotary sleeves, the ergonomic requirements changed drastically. In order to operate those sleeves by one hand only, without removing the instrument from the mouth, a finger needed to push the knob upward from its sideward position to close a hole, and downward from the top to open it. The latter procedure is comparatively straightforward, because the forces are directed downward and "outward," toward the hand, where the thumb and the other fingers can easily provide the necessary counterforces. When shutting a hole, in contrast, the forces that need to overcome the friction of the tubes work upward and "inward," away from the hand. Here the upward element can again be counterbalanced by fingers resting on the tube. The inward component of the force, however, might easily push the pipe from the grip of the hand when the fingers are stretched (as they must be for larger spans) and the angle between fingerholes and thumbhole at the side of the hand is smaller than 180°. Displacing the thumbhole to the other side remedies the problem: the center of the tube thus comes to lie inside the enclosure of fingers and thumb, where it is safely secured.

In this way, it appears that the evidence can be fully explained on the basis of an ergonomic interpretation, in the frame of a historical model that posits adaptation only where there was evident need for it. As a side effect, this interpretation reinforces the idea that the sleeves were actually rotated during performances. As long as no contradictory evidence surfaces or a convincing explanation for switching high and low pipes between the hands is found, we should accept as most likely that this particular type of aulos enabled modulation between keys or even change of hand position without stopping the music, with the knobs of open holes typically pointing toward the palms, and of closed holes, upward.

7.1.2.7. *Playing Together?*

Being tuned to similar reference pitches and designed for the same system of keys connected by the circle of fifths, the two instruments S1 and S2 would have experienced little problems performing

55. Only once do we find the requirement of swift manual action when switching between keys on the aulos mentioned: Philostratus, *Life of Apollonius* 5.21: καὶ γὰρ τὸ ταχέως μεταβάλλειν ἐκ τρόπου ἐς τρόπον περὶ τοὺς εὐχειράς ἐστι μᾶλλον "rapid modulation from key to key is also associated rather with fine hands." However, this might still be taken to refer to quick change of configuration during short breaks in the music. See Hagel 2009a: 337 n. 28.

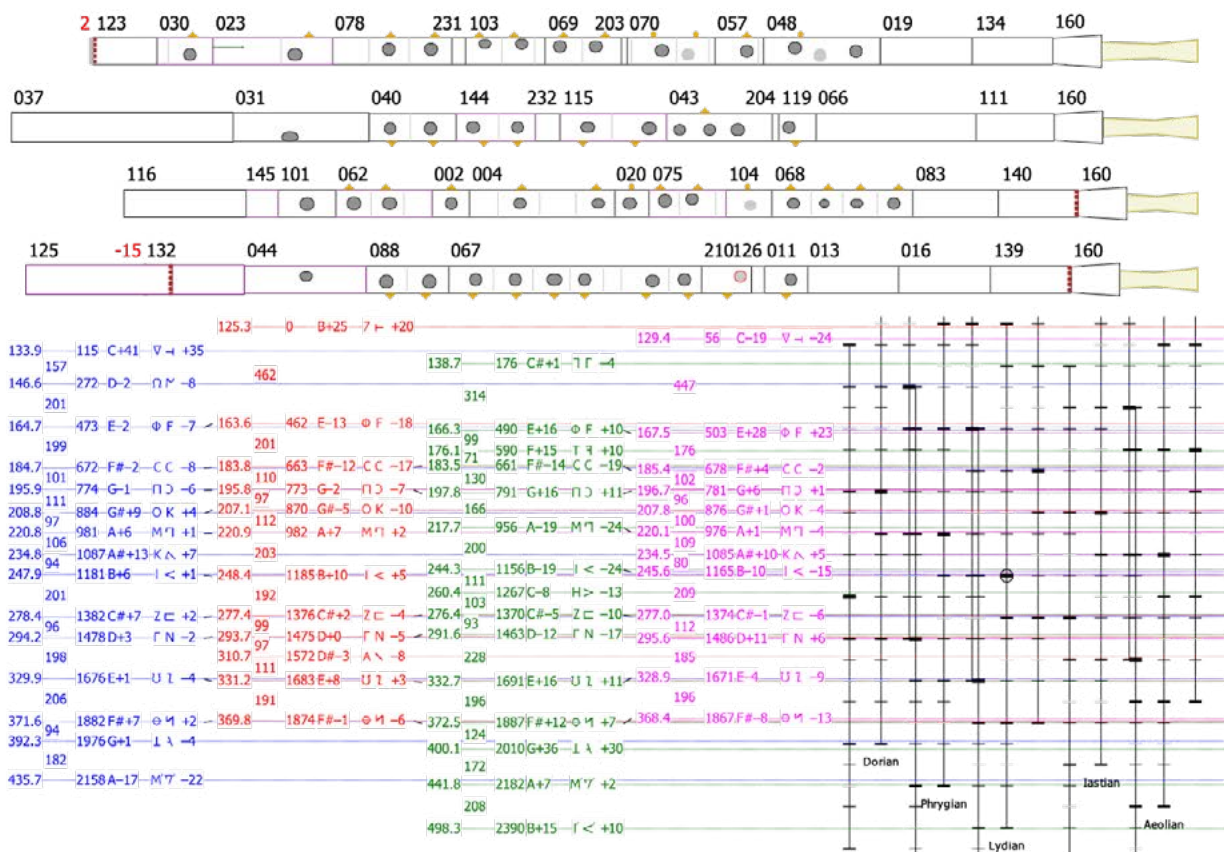


Figure 7.21: Optimized pitches and intervals for the full set of S1-H (reed: 51.3 mm), S1-L (reed: 50.5 mm, and S2-H (reed: 37.8 mm), S2-L (reed: 41.6 mm). Holes below: one closed if the interval is smaller than three quartertones, \ominus closed when playing $\lambda = \perp$; Lydian *hyperbolaia*: 494Hz (490Hz+15 cents); harmony: 300/22/12/15/10 (threshold 20 cents).

together. Figure 7.21 presents optimized reed lengths for such an ensemble and facilitates comparison of the respective harmonic potentials of the two auloi. One will once more note the full or partial omission of the same notes on each: $T=Y$ ($C\sharp$), K ($g\sharp$), $H=\Theta$ (bb), A ($c\sharp$), $\mathfrak{h}=\mathfrak{X}$ (eb') between \mathcal{U} and Θ , and \mathcal{O} ($f\sharp'$) below \mathcal{M} . In this case, at least, the conspicuous pairing of instruments of similar design may therefore reflect paired performances before the deposition, probably in the service of the deceased Queen.

While the musical interpretation of the two instruments thus appears well-founded, the delicate nature of spacer rings may cause us to miss some information crucial for an actual reconstruction especially of S2. For instance, the intonation of the lowest toneholes of S2-L would benefit from a spacer of about 3 mm, inserted either between 044 and 088, or more plausibly between 088 and 067. Similarly, the apparent mismatch between the reeds of S2-L and S2-H might be counterbalanced by a ring above 011.

7.1.3. The Slender Pipes with Wood Core

7.1.3.1. Reconstruction

An interpretation of the simpler quartet may start from 015, one of the most outstanding pieces of the collection, being the only section with five fingerholes, thus defining an entire hand position. Interestingly, it does not include a proper thumbhole, but instead a second hole for the index finger, positioned half a centimeter lower and shifted toward the right side of the tube, so that the index finger of the right hand could stop or open both holes at once, but also uncover only the hole at the side. A similar design has been observed on instruments from Pompeii.⁵⁶ A thumbhole is instead missing. What

56. Naples National Archaeological Museum inv. 119890C; 76894.



Figure 7.22: Item 059, upside, left = downstream.

has prompted such an unusual arrangement? Without doubt, a thumbhole could have been drilled at the same position; consequently, we must assume that the double-index solution was preferred by the musician. The presumable reason must be that a thumbhole is always more difficult to operate since the thumb at the same time supports the instrument. However, a design with two index-finger holes is only possible when the distance between the two highest holes is minimal; otherwise, the index finger cannot possibly close both at once. Indeed, all the fingerholes on the present section are unusually closely spaced, with an overall finger span of only 7.15 cm—the long pipes to be discussed below require more than twice that span, while about 12 cm is typical for normal-sized instruments.

A sequence of five very closely spaced holes can only mean that the pipe played at comparatively high pitch. On the highest of the four bronze-silver pipes from Pompeii, comparably spaced holes reach up to 540 Hz.⁵⁷ Here the respective piece is broken at its upper end, but if set to the same region it might be complemented without too much loss by part 018 and leave just enough space for a slender bulb such as 156 and a reed seat such as 160 in order to play in that region with a reed extending about 3 cm from its socket. Since all other hole distances in the simple pipes are significantly larger and would therefore hardly be positioned higher, we may conclude *a fortiori* that each of them could accommodate a bulb.⁵⁸

With all fingers assigned to such a high position and no mechanism for closing holes, we must expect a significant extension of tubing below the fingerholes, visually balancing the other pipe in the pair. The respective tubing would feature no more than a single tonehole.

Item 015 is not the only remarkable piece. The section 073 contains the topmost three fingerholes of a pipe at the lower end of a long tube, the holes being almost equally spaced. They are so close together that they cannot have played much larger intervals than two semitones. Item 059 is similar, but the spacing of the holes is wider and the tube shorter. Most importantly, its middle-finger hole is elongated upward, where it terminates in a sharp corner, resulting in an elegant teardrop shape (fig. 7.22). Obviously this helped producing more than a single note from this fingerhole by either opening it completely or exposing only part of it by pulling the finger upward. The shape also defines the orientation of the piece, since the narrowing end must point upward: uncovering a fingerhole naturally starts at the lower end, toward the other open toneholes and the exit, and it should immediately produce some significant aperture lest the pipe should squeak or stop sounding entirely.

We have already mentioned the remaining thumbhole on 021, which must have been part of another, fourth, pipe. Around these cores, eight pieces with single holes need to be arranged, one of which resides in a long bell section. Then there are three more bells, confirming a total of four pipes, and six spacer tubes of various lengths. A further tube with broken end may have formed the lost top of 073, though no physical connection could so far be established.

The combination of bell part 025 with item 113, which an in situ photograph from the excavation preserves (see below), demonstrates that the lowest tonehole of such a pipe may have been removed from the end by as much as 14 cm. Consequently it is not necessary to posit a lost hole in the missing wall parts of the long bell piece 120, even though the possibility cannot be excluded either.

57. See Hagel 2008.

58. The contrary assumption expressed in Hagel 2019: 182–83, based on corrosion patterns, needed to be revised after detecting a section on an old photograph that had meanwhile disintegrated (133).

In spite of the relatively small number of parts in the puzzle, I have found no straight logical alleyway toward a convincing reconstruction. One needs to take clues from corrosion patterns, which may be tantalizingly seductive and still misleading, but also from patterns of deformation, while some combinations might be excluded thanks to small differences in external diameter which it would have been impossible to obscure on the shiny instruments those pieces had once been—on the other hand, the different states of corrosion often preclude a sufficiently precise assessment of those diameters. The puzzle requires assigning precisely five or six holes to each pipe and completing them upward up to closely matching extensions, while at the same time establishing a satisfying number of both shared pitches and harmonic intervals between the notes from each pair, assuming reeds of a plausible size attached to pipes whose fingerhole spacing is physically manageable. Ultimately there may be more than one solution that matches all criteria, but potential solutions would probably still share many if not most musical characteristics. At any rate, I have only been able to find a single convincing solution with the available material; and the chances are slim that the evidence might yield another significant part. However, I still cannot offer a consistent argument that would settle the matter once and for all, including ruling out the complete loss of one or more substantial sections.

The hypothesis presented in the following includes the counterintuitive assumption that the more widely spaced holes of 059 are placed higher than the closer group on 073, but this appears inevitable given the long tube of the latter. The proposed arrangement is anyway supported by the opposite displacement of the thumbholes, toward the right on 059, but to the left on 073. As discussed above, on the earlier aulos types without modulating sleeves and only a limited number of fingerholes, leftward thumbhole displacement is regularly associated with the lower pipe of a pair, so 073 is rather expected to come from a lower pipe. Its upper end is broken; the short item 035, also broken at one end, forms a plausible supplement even though no physical joint can be established; the preserved lengths of the two parts may have overlapped up to 6 mm. Spacer 012, in turn, complements 059 in a way that its middle-finger hole coincides with the index hole of 073. Below 059, part 060 continues the corrosion patterns seamlessly, suggesting a common history in the soil. At the same time, its hole corresponds to the middle-finger hole of 073.

Continuing 073 downward, no piece suggests itself as much as 045, the pitch of whose fingerhole can once more be matched by attaching 081 below 060. The smashed end of 081, in turn, suggests adding the half-broken rim of bell 120, resulting in a perfect bass note, a fifth below 081, and an octave below the middle finger on 059, if provided with a reed of the right size. Below 045, bell 091 with its integrated fingerhole or alternatively the in situ compound 025+113 with bell and fingerhole would both add a musically useful fingered note but a problematic bass note—and the hole on 091 would hardly be manageable for the little finger, given the long distance to the ring-finger hole as well as the proximity of the three highest ones. A much better choice is the combination of 142 with bell 107, separated by the destroyed spacer tube 133. The latter had totally disintegrated before the start of our project, but we were able to infer its existence and dimensions from a photograph published by Bodley and finally to identify a few parts that confirmed its total length.⁵⁹ The extent of the bell of 107, in turn, must be established from the excavation photograph (fig. 7.23). Together the three sections extend the pipe to the length of its counterpart; no other option appears to complement the instrument meaningfully. The combination of 107 and 133 may also be encouraged by the fact that their combined lengths are practically identical with that that we will below establish for bell part 025. The number of mutually confirming coincidences strongly suggests interpreting the two pipes as a pair; at least, I have not been able to establish comparable matches with other parts.

This leaves us with 113–025, 105, and 109, as well as the hole in bell 091, to complement 015 and 021. We remember that 015 already supplies holes for all fingers, so its pipe may only have included

59. Confusingly, Bodley refers to this item as a “rotary sleeve” (1946: 233), even though it neither featured a hole nor, apparently, any sign of internal tubing. On the photo, the part appears a trifle longer than Bodley reports. The difference is of no musical consequence (in the evaluation below, it corresponds to a difference of 5 cents in a single bass note).



Figure 7.23: Section 107, with parts of the lower rim of its bell still preserved.

one more tonehole. Apart from the end pieces, the items are all conspicuous for their shared “stripy” corrosion patterns.

The distance between the holes in 021 does not musically match any on 015; therefore any overlap between the fingered notes might only start from the higher hole of 021 upward. Since 021 contains a thumbhole, such an overlap can therefore involve only one more hole for the index finger. If we demand reasonably precise pitch coincidences within the overlapping region, the upper hole on 021 would need to form the thumbhole. This is anyway demanded by the relative orientation of its two holes, in an argument that is luckily independent of the question which of the holes faced upward, thanks to the nature of chirality. Thus, if the two nearly opposite holes would include the index hole in addition to the thumbhole, the section would form part of a right-hand pipe; conversely, if it contained the holes for thumb and middle finger, it was part of a left-hand pipe. Since the rightward-displaced secondary index hole of 015 can only be played with the right hand, 021 should however belong to the left hand. Consequently its holes must have been meant for thumb and middle finger, so that another section with a single hole for the index must have been placed above it.

Either 105 or 109 might serve the purpose, potentially establishing an interval that matches the lowest interval on 015 with acceptable precision. The corrosion patterns are of limited help because among the pieces in question, most combinations appear to match in one way or other; but the particularly squashed shape of 105 would sit weirdly between the round tubes of 021 and the required upper spacer, while 109 fits well in this place. Section 105 thus needs to go below 021.

However the pieces are arranged, the fingered portion extends so far downward that adding the long bell of 091 would deprive the set of any balance. The correct bell piece would therefore be the combination of 025 and 113, the latter providing a convenient little-finger hole. This leaves 091 to terminate the right-hand pipe, obviously requiring more tubing in between, without any fingerhole.

In order to determine the correct spacers, we must first look at the upper ends. Here the broken end of 015 may once more be complemented with another tube fragment with only one partially intact end, which we find in 018. Careful inspection shows that the broken ends of the two may overlap by as much as about 14 mm. Another broken tube, 074, would fill the gap above the compound that includes 021, assuming a loss of about 9 mm. The remaining spacers are 014 and 084, which look very similar. Inserted between 015 and 091, they once more produce a pipe of the same length as its counterpart—at least roughly, given that the original extent of 025 is not certain.

From the required reed lengths, which we will discuss below, it appears that the formerly established pair needs shorter bulbs plus reed cones than the latter; it seems therefore reasonable to assign bulb 156 and its almost entirely lost counterpart 148 to the latter, and bulbs 064 and 157 to the former.⁶⁰ The remnant of 148 appears to feature a *syrinx* hole, right in the region that would have been covered by silver. The destroyed parts of 156 and 157 may have held similar openings; contrarily, 064 probably had none.

60. The severed distal end of bulb 064 had wrongly been inserted into tube 059 at least from Bodley’s time on (Bodley 1946: 230 and Tab. 5.9; Hagel 2019: 178); once separated, it became possible to reconnect a piece to its distal end that could hardly have come off had the part always been inside 059.

Again, we can now tentatively define two instruments, labeled W1 and W2: 021 → W1-L, 015 → W1-H, 073 → W2-L, 059 → W2-H.⁶¹ The pipes' handedness is nicely borne out as expected, the higher ones being assigned to the right hand by the relation between index and thumbholes on part 059 on W2-H as well as, unmistakably, the double index hole on 015 on W1-H, while thumb and index holes on 073 on W2-L are arranged in the opposite way. The estimated total lengths (without reeds) would measure: W1-H: 446.2 mm; W1-L: 450.0 mm; W2-H: 452.0 mm; W2-L: 456.3 mm.

7.1.3.2. Interpretation

7.1.3.2.1. General Considerations

These “wooden” instruments, as we have come to call them for lack of a more precise succinct term, are unlike anything music archaeology has seen before. While their general construction, wood encased in copper alloy with a bone bulb, finds parallels in Pompeii, their fingerhole arrangement, in which closely packed segments contrast with others of wide spacing, does not. As we will see, the widely spaced parts might encourage a pentatonic interpretation—anhemitonic pentatonic, that is, in contrast to the hemitonic pentatonic that forms the intersection of the three ancient genera.⁶² Anhemitonic pentatonic is still at home in many music cultures, including large parts of Africa; consequently one might wonder whether these instruments, at last, testify to local musical traditions. On the other hand, at least the wood from which the pipes were made was evidently of Mediterranean origin, and the bulbs and reed cones are of the same make as on the instruments with mechanism. Equally importantly, the sequences of narrow intervals that are also present do not sit easily in a pentatonic musical environment, least of all the teardrop-shaped hole that must have been designed to sound pitches significantly less than a tone apart.

If, on the other hand, the instruments were meant to play music that ancient Greek theory would

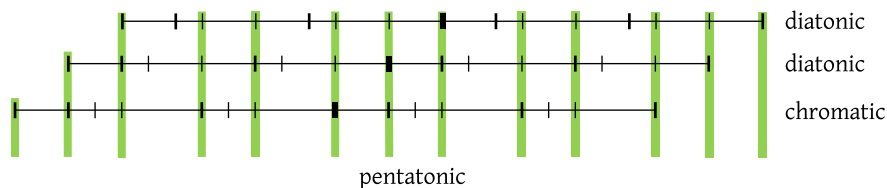


Figure 7.24: Projecting an anhemitonic pentatonic scale onto ancient diatonic and chromatic scales.

have called “chromatic,” it is possible that the pentatonic characteristics are but a side-effect of a chromatic design. After all, when the middle notes of each chromatic triplet (*pyknón*) in a regular chromatic scale are omitted, the result is a pentatonic structure (fig. 7.24).⁶³ Therefore, whenever such *pykná* were meant to be played bisecting a tone by half-covering a fingerhole, the resulting pipe design would look (and be) anhemitonic pentatonic. Ockham’s razor therefore suggests not to embrace a pentatonic hypothesis in addition to chromatic traits where the chromatic is evident and can explain the pentatonic structures as well.

Although numerous fragments of wood have survived, partially in place, they do not lend themselves to reliable measurements, least of all of the bore diameter. We must therefore assess the internal diameter of each pipe from that of its bulb. However, while we had good reasons to assign each of the three extant bulbs to one of the instruments, their distribution between the pipes of each instrument remained unclear. At any rate, bulbs 064 and 157, which must belong to the same instrument W2, are practically identical, so that exchanging them does not affect the calculations. Accordingly we have reason to assume

61. These are now assigned the following accession numbers: 24.3586 (W1-H), 24.3587 (W1-L), 24.3588 (W2-H), 24.3589 (W2-L).

62. For the latter, see Aristoxenus, *Harmonics* 2.44, p. 55.10–11 Da Rios; see West 1981; Hagel 2000: 38–39 with n. 61.

63. Note that pentatonic can be extracted from diatonic in two different ways, by omitting the upper or the lower boundary notes of the semitones (the first being much more natural in the context of Greek harmonic theory), while the relation between pentatonic and chromatic is unequivocal—but again different, in terms of matched scale degrees, than either of the diatonic options.

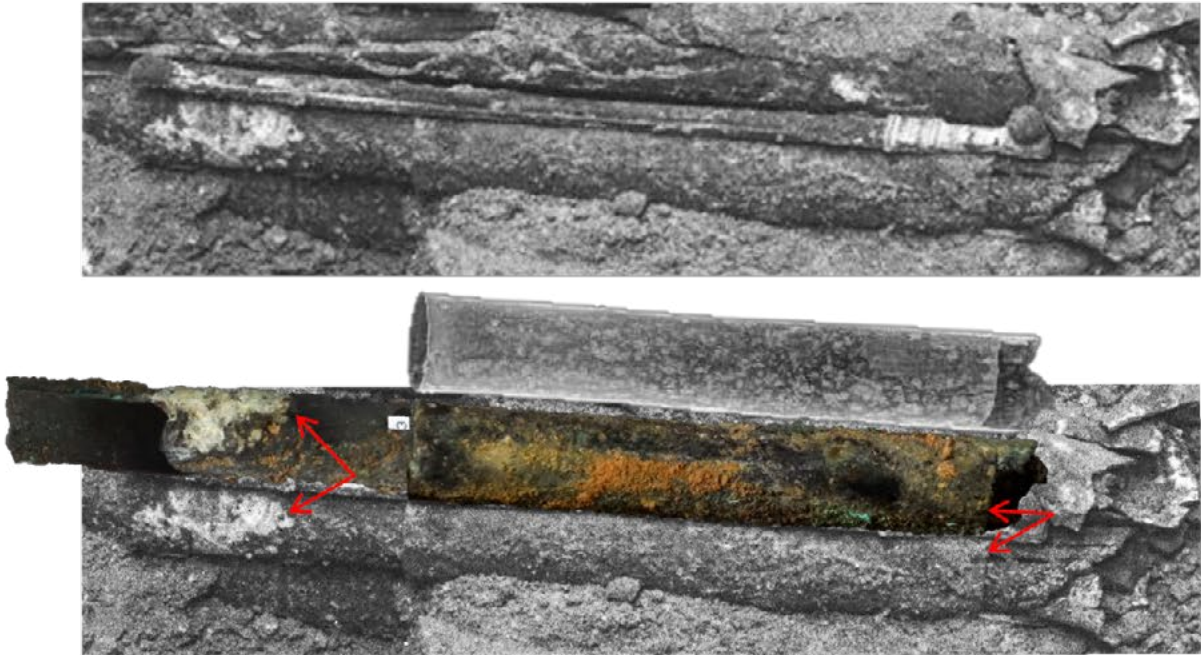


Figure 7.25: Items 133 + 025 in situ and in comparison with recent photographs (color) and a radiograph (gray tube above the colored).

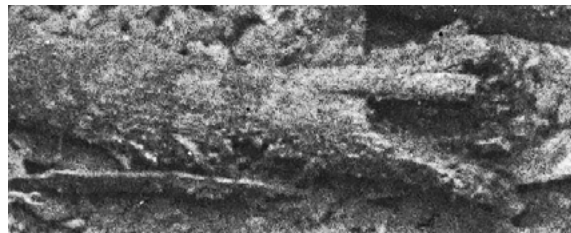


Figure 7.26: A brighter seam on the wooden core of 015?

that the two bores of W1 were also sufficiently similar and can be gauged from the sole remaining bulb 156, which is just slightly narrower than the others (7.5 mm vs 7.7–7.8 mm).

7.1.3.2.2. *Instrument W1*

On the higher-pitched pair, we observe a shift of three fingerholes between the two hands, which is as much as on the Louvre aulos or on S2 (though there not associated with the primary playing position, indicated by the thumbhole). But that is as far as the similarities with other known instruments go.

The details of an evaluation depend on the tantalizing question of the original length of the end piece 025. As discussed above, its bell is lost but clearly discernible in one of the excavation photographs (fig. 7.25). Nonetheless it may not be justified to assess the missing length from that image, depending on whether the flaring part beyond what now remains of the section continues the metal encasing or rather represents the remnants of the wooden core. Originally we had leaned toward the latter assumption, guided by the impression of a reduction in diameter. On the other hand, it seems just possible that the metal of the bell end, on one side broken from the main tube along a surprisingly smooth line, was only pushed a little further in. A metal bell would allow measuring the missing part quite precisely, while a wooden core, once shrunk, may have moved from its original position, as it had obviously done in item 015, further up on the same image. The first option would provide us with a very precise value for the original length of 025 of about 105.5 mm.

On the other hand, while it is difficult to make out any fibers on the photograph, a brighter seam along the broken rim might encourage the interpretation of a wooden core whose encasing has crumbled, since a similar phenomenon can also be observed on the wood of 015 (fig. 7.26); on metal, in contrast, it would

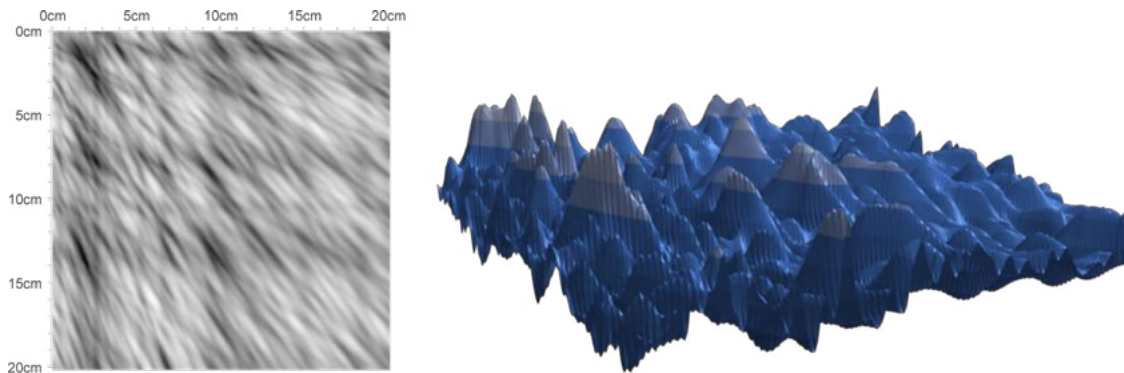


Figure 7.27: Harmonicity map of instrument W1 with maximal length of 025, as a color map and an elevation chart within the surveyed 20 cm × 20 cm space. Fingerholes below open; Gaussian evaluation ($\sigma = 10$ cents). Design: S. Hagel.

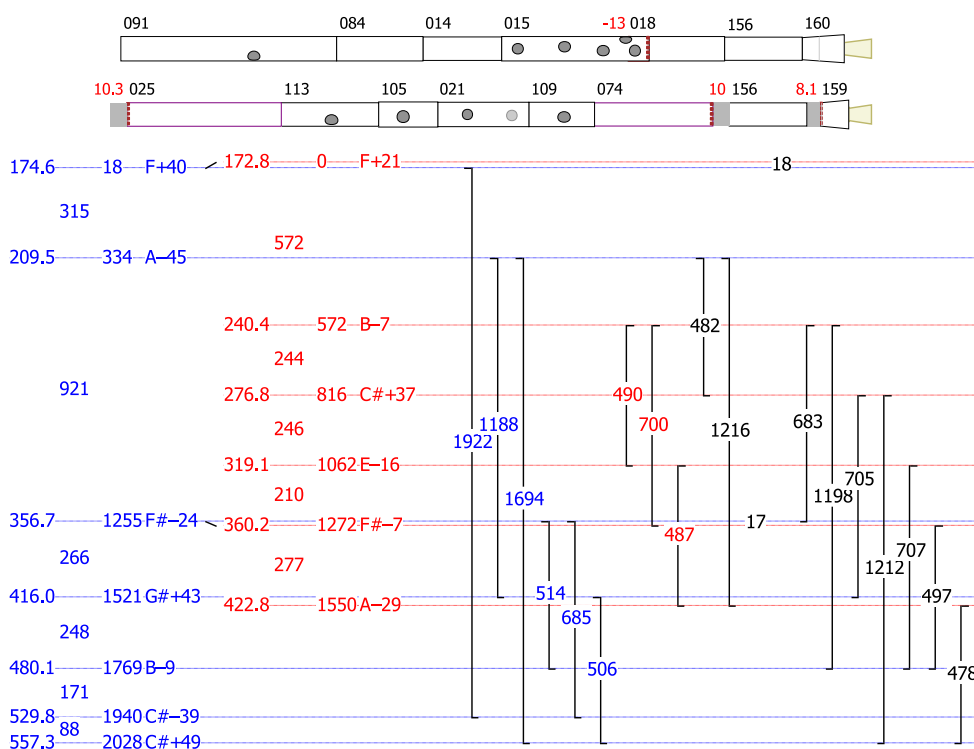


Figure 7.28: Inferred pitches and intervals of W1 with maximal length of 025; holes below: open; harmony: 11/6/3 (threshold 20 cents).

be atypical and difficult to comprehend. If the image does show a wooden core, the minimal original length of 025 would only be determined by the length of the bell itself, since most of what remains of the piece is clearly straight tubing. Judging from extant bells—for example, that of item 120—the piece might have been as short as 100 mm. This would also reduce the difference between the ends of the two pipes to the visually and musically negligible amount of no more than the twentieth part of a tone—only a couple of millimeters from predicted unison, assuming two common fingered notes as discussed above.

The harmonic analysis accordingly appears to support the latter option. While a longer bell produces no pronounced maximum (fig. 7.27), the shortest possible bell does so nicely (fig. 7.29), also reflecting a higher number of reasonably pure concords (compare fig. 7.30 with fig. 7.28).

While the extent of the lower ends thus appears settled, the original length of the upper spacer tube of the lower pipe, which is broken at one end, can only be gauged from the desirable acoustic length

Anyway the treble intervals require special attention, because it seems quite possible that the figures from a model with open holes throughout might here not completely reflect the intentions of the musicians. The apparent sequence of a very small tone and a semitone (168+86 cents), at least, would be difficult to reconcile with any ancient scale, nor would a sequence of two functional semitones where the higher is significantly smaller.⁶⁵ We must instead take the special possibilities and restrictions into account that come with the secondary, laterally displaced index hole. On the one hand, its pitch in open fingering seems to have been carefully chosen, placing it just a twelfth above the bass note—arguably the second purest interval after the octave. On the other hand, opening it completely while keeping the top hole sealed is not totally straightforward. Since this had to be achieved by stretching the finger that had been curved around the tube when sealing both holes at once, the finger would typically not recede very far from the tube surface and therefore still reduce the effective opening, thus flattening the tone. This may have been an intended effect because the region where the lateral hole could be functional is extremely limited by the physiology of the hand (an alternative way of achieving a larger interval would be to drill that hole smaller). Closing the middle–finger hole when opening the lateral index hole would have increased the effect, but also the risk of squeaking because it may have been difficult to uncover the lateral hole quickly enough. All in all, it appears not unlikely that the two intervals in question were intended to be, at least sometimes, of a more equal size than a naïve analysis would suggest, approaching what ancient theory might have called a very “tense” (meaning: wide) chromatic *pyknón*. Furthermore, it is possible to open only the top hole while keeping the side hole sealed. This flattens the treble note so that the interval to the middle finger decreases to a tone (predicted 206 cents), and consequently that to the lower common note, to a fifth. With appropriate cross-fingering, the close triplet of fingerholes may thus have served three alternative harmonic functions: a chromatic *pyknón* of a particularly wide type, a whole tone of the sort that complements tetrachords to fifths, and a perfect consonance to the bass note.

The two notes below are present on both pipes, and appear tuned in excellent unison, as would the two bass notes. However, in order to access the note from the exit of the higher pipe, one would need to plug the vent hole on 091, which may or may not have been an option the ancient players of this instrument considered. The remaining notes produce various concords whose integration within a comprehensible system does not immediately spring to the eye.

At any rate, if the two intervals at the top represent a kind of chromatic *pyknón*, the interval below complements it to a fourth. Although this would represent a “tetrachord” in an old and general sense, still used indiscriminately in Aristoxenus, it is no tetrachord in its standard “citation” form (where the *pyknón* would sit at the bottom), but the so-called third shape of a fourth.⁶⁶ As a corollary, in order to become part of a more extensive scale, the lower of these intervals needs to be classified as the highest of another chromatic tetrachord, which extends downward starting right from the lowest note of the *pyknón*. This is borne out by the five–quartertone interval below it, which is just as large as the total upper *pyknón* (in fig. 7.30, 263/274 cents vs 168+86=254 cents). Not being bisected by another fingerhole, it might either be considered a kind of “gapped chromatic,” or one might have played the central note by half-covering. The analysis as a conjunct sequence of two chromatic tetrachords, the upper lacking its top note, is supported by the next interval: below two conjunct tetrachords, a regular scale would normally need a “disjunctive” tone (mathematically 204 cents), as we find it implemented on the lower pipe (predicted 205 cents). The ring-finger and little-finger notes on the lower pipe might then form just another “gapped chromatic” tetrachord, playing in octaves with the index and middle–finger holes of the higher pipe. The structure is complemented by the vent hole, again on the higher pipe, and the bass notes, on both, which apparently supply the octaves to the notes that are present on both.

In the form of tetrachord—disjunctive tone—tetrachord—tetrachord the instrument would thus implement a large part of the Greater Perfect System, from *hypátē mesón* up to *paranētē hyperbolaíōn*, omitting merely one tetrachord downward, while upward stopping short only of its highest note, *nētē hyperbolaíōn*.

65. Such a configuration is avoided by all theorists and explicitly denounced by Ptolemy, *Harmonics* 2.13, p. 68.27–29 Düring.

66. See, e.g., Aristoxenus, *Harmonics* 3.74, p. 92.12–17 Da Rios (expressed in enharmonic terms); Cleonides 9, p. 195.8–15 Jan. Where Aristoxenus talks about the “standard form,” he needs to define it explicitly, such as in *Harmonics* 1.22, p. 28.10 Da Rios.

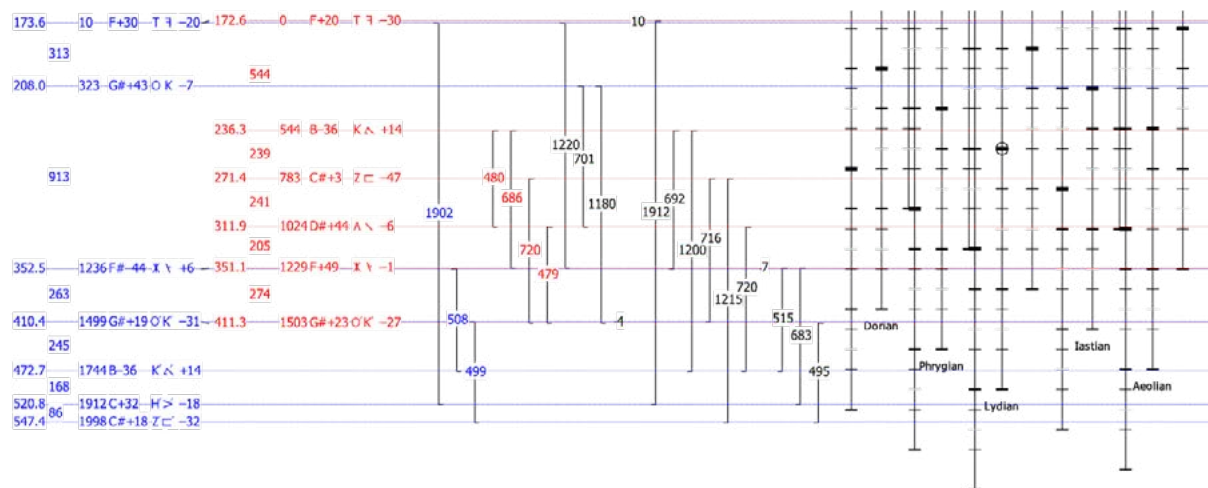


Figure 7.31: Pitches and intervals of W1; holes below: open, thumbholes closed; Lydian *hyperbolaía*: 496Hz (490Hz+20 cents); harmonicity: 15/3/4 (threshold 20 cents).

However, even this note is actually accessible. Being situated a twelfth above the vent hole, it sounds when the cylindrical pipe is overblown while all fingerholes are closed and only the vent hole remains open. A fitting reed will easily overblow in the course of melodic moves between the high notes, because the pitch difference between a treble note from the fingerholes and an overblown bass note requires a smaller adjustment of the oscillatory regime than would the pitch drop to the fundamental pitch of the same bass note. Otherwise, opening up a tiny aperture at the rim of the index hole would facilitate overblowing, just as on modern instruments. Curiously, the same organological trick of a high chromatic tetrachord whose large upper interval, so unwieldy for the human hand, is effected by overblowing appears to be found on an instrument unearthed in the Vesuvius region, almost precisely at the same pitch.⁶⁷

All features of the instrument thus appear to find a reasonable explanation without violating the tenets of ancient Greek harmonics. We might posit two different modes of playing it: with the vent hole open, the highest tetrachord is fully available; after plugging the vent hole by some means, the lowest tetrachord is better supported. It may also be significant that the vent hole itself provides the scale's *hypérypátē*, in its true nature of the “*diápemptos*” a fifth below *mésē* and thus a disjunctive tone below *hypátē*.⁶⁸

In addition to explaining the internal structure of the instrument by reference to the abstract scheme of the Perfect System, is it possible to assign its specific pitch to one of the ancient keys? Perhaps not: the notes on which such an ascription depends sit squarely between those in the semitone grid of the more ancient *tonoi*. Judging by a reference pitch of 490 Hz, the aulos appears closest to Hyperaeolian, coinciding with it at the slightly higher standard that we found realized on the previously discussed instruments (fig. 7.31). While a Hyperaeolian interpretation might thus appear worth considering on purely structural grounds, this key is otherwise rather elusive. Most importantly, it did not even form part of the traditional thirteen Aristoxenian keys but was only introduced in the final stage of ancient notation, probably postdating the era of Amanishakheto. Therefore, this aulos might just as well have belonged to the class of wind instruments that were merely tuned within themselves, following the tenets of the tetrachordal system and ultimately the Perfect System, but without pledging allegiance to any particular *tónos*, similar to, apparently, the Berlin aulos.

67. Wyslucha and Hagel 2025: 156–61.

68. In a chromatic context, this *hypérypátē* differs from the *likhanós hypatón*, with which it has often been confused, due to their identical pitch in the most important, diatonic tunings.

At any rate, high pitch and the chromatic genus were both associated with the music of grief and lament.⁶⁹ No aulos may thus have been better suited to the threnodic aspects of a royal burial than instrument W1.

7.1.3.2.3. Instrument W2

The harmonic evaluation of the other aulos faces the conundrum of a teardrop-shaped hole. Quite apart from the potential inaccuracies involved in assessing its area, it may not even be most helpful to know its pitch when it is fully open: in sequences of notes separated by very small intervals, it is typically the lowest that is defined by the larger harmonic structures of ancient Greek music, while the others depend on matters of fine tuning and are therefore subject to variation related to musical styles no less than historical or regional fashion. For this reason it might appear advisable to close the pointed part of the hole for a first assessment, even though the amount by which this would have been done can only be guessed. A quick simulation shows that the pitch difference gained by opening or stopping an area corresponding to the narrow part of the teardrop—that is, the difference between the total area and that of an extrapolated symmetrically round hole—amounts to quite precisely a quartertone (predicted 52 cents). Covering a larger part would increase that pitch difference, which can however serve as a reliable minimum. If the aulos was built for such an enharmonic interval, a harmonicity assessment based on the fully open hole would indeed be misleading, as it is to be expected that the resulting pitch would not harmonize with any fully open hole.⁷⁰ When a larger portion of the hole was covered, on the other hand, the pitch difference would of course become larger, perhaps up to a semitone or a little more, before the opening would become too small and the oscillation unstable. Assuming an intended step of a semitone, the fully open hole might have been of no lesser harmonic importance than the half-covered pitch, since both might have belonged to different keys. However, the thumbhole above the teardrop-shaped middle-finger hole must have sounded about another quartertone above the latter when fully opened. Greek theory, at least, knows of no succession of semitone and quartertone: the latter may only be found above functional ditones, tones or other quartertones. Even in Ptolemy's enharmonic, where one of the supposed “quartertones” is almost twice the size of the other, retaining the smaller interval at the bottom is considered crucial.⁷¹ Nor do other musical traditions appear to contribute to the understanding of such a pitch structure. As a result, it seems we must start the evaluation from a partially covered teardrop hole, in the proposed way of retaining an open area equivalent to a symmetrical hole. Consequently, opening its upper part will result in bisecting the interval to the next higher hole.

For this configuration, the automated optimization produces about the same number of consonances than on W1, in spite of the overall closer spacing of holes on the tubes of W2. Within the surveyed reed lengths of 0–20 cm, we however obtain, instead of the accustomed unique maxima, several peaks of substantial height (fig. 7.32). Of the two largest, one can safely be discarded as unrealistic, as it combines a reed of 3 cm with another of over 19 cm; the other is also the only to warrant reeds of sufficiently similar lengths.

In spite of their limited abundance, the consonances are all the more promising (fig. 7.33). Above the bass notes we find octaves, which are structured into fourths and fifths from above and below; all these consonances are available as simultaneous sounds. This kind of divided octave is the *harmonía* that Philolaus described in the Classical period and that still formed the foundation of all the lyre tunings specified by Ptolemy in the second century CE.⁷²

69. For chromatic as mournful, see Sextus Empiricus, *Adversus Mathematicos* 6. 50; Theon of Smyrna p. 55.4–7 Hiller; Bellermann's Anonymi §26; and the paragraph found in the manuscripts after the end of Book 2 of Aristides Quintilianus (p. 92.19–30 Winnington-Ingram).

70. It would correspond to a *mesópyknon*, that is, the harmonically weakest note between two nominal quartertone steps. As far as we see, in the fingered region of an aulos such pitches were achieved by half-holing, a technique that is assumed to have given rise to the designation of the small interval as *díesis*, “letting through” (West 1992: 235 n.42), even though below the reach of the playing hand individual bass holes may have been provided for them (Terzēs and Hagel 2022).

71. Ptolemy, *Harmonics* 1.15, p. 34.5–35.4 Düring; cf. n. 65 above.

72. See Hagel 2009a: 112–16.

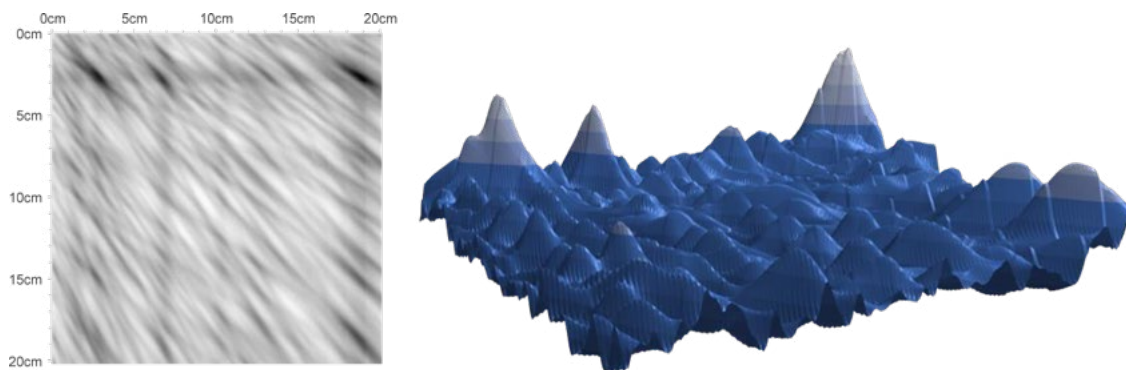


Figure 7.32: Harmonicity map for instrument W2, as a color map and an elevation chart within the surveyed 20 cm × 20 cm space. Fingerholes below: open; Gaussian evaluation ($\sigma = 10$ cents). Design: S. Hagel.

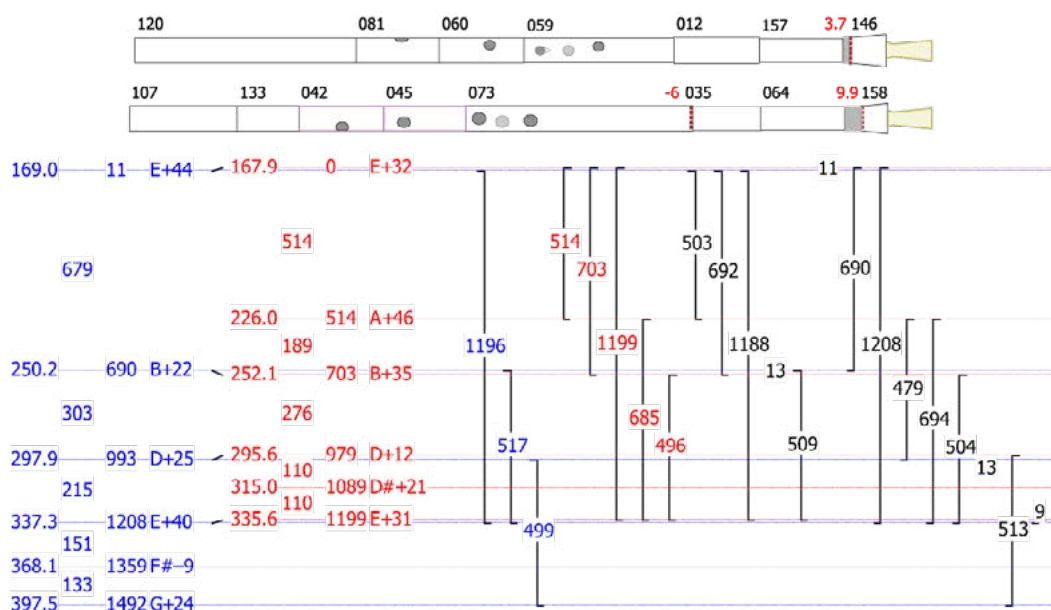


Figure 7.33: Inferred pitches and intervals of W2-H (reed: 27.5 mm) and W2-L. Holes below: open; teardrop-hole: edge covered; harmonicity: 14/3/5 (threshold 20 cents).

None of the two respective fourths appears as a tetrachord of the standard form. The lower remains undivided, at the bottom of the gamut. The higher is once more shaped as the “third species” of a chromatic tetrachord, with the *pyknón* at the top,⁷³ just as the one we have encountered at the top of W1-H. How is such a mismatch between the structures possible, given that the tone in the center of the divided octave should be expected to define the shape of its adjacent fourths? Actually we are familiar with such shifts between the fundamental structure of the octave, on the one hand, and the functional tetrachords of scalar analysis, on the other, from the transmitted cithara tunings. To describe these, Ptolemy notoriously distinguishes between “function” (*dýnamis*) and “position” (*thésis*). The former describes the musical identity of a note in relation to the abstract Perfect System, while the latter refers to the position of its string on the instrument. The two can coincide only in a single *tónos*, since any change of key shuffles the functions of the pitches around the circle of fifths. Nonetheless every tuning, in any of the four used *tónoi*, retains the same structured octave with fifths and fourths from the extremes and consequently a well-defined “disjunctive” whole tone in the center. In all the *tónoi* in which this “positional” tone does not coincide with the “functional” disjunctive tone, it must instead implement one of the many other

73. See n. 66 above.

whole tones within a diatonic scale. Whichever takes on that role must then assume the precise size of a disjunctive tone as well ($9:8 = 204$ cents). This dictates various compromises when the favored shade of diatonic must give way to the simple old diatonic of perfect fifths and fourths throughout. Ptolemy gives no chromatic example because his single chromatic cithara tetrachord, in the tuning *trópoi* that we have already mentioned, fell comfortably in one of the “regular” slots.⁷⁴

On our aulos, we seem to observe an ingenious chromatic solution to the same problem. Again, it is based on equating the precisely defined “disjunctive” whole tone in the octave structure with a tone within a tetrachord that might otherwise be tuned to diverse sizes. In the chromatic, whose tetrachords are formed from “semitones” of different sizes and the remainder of about a minor third, there is of course no incomposite interval of the size of a tone other than the obligatory disjunctive tone between tetrachords. However, when taken together, the two “semitones” may comprise just the same size—and they do so by definition in the standard handbook definition of the chromatic. Just as in Ptolemy’s diatonic tunings, compatibility between the structures thus enforces the adoption of a particular “shade,” in this case “tonic chromatic,” to the exclusion of all others. This seems to define the design of our aulos: the whole tone at the center of the octave, as we have seen, lies beneath the upper interval of a chromatic tetrachord, where we expect a *pyknón*. Its internal division would need half-covering the hole for the left ring finger. In order for the division to work out, so that the interval above the tone=*pyknón* complements it to the fourth of a complete tetrachord, the size of the higher *pyknón* must also conform to the same size. In the virtual reconstruction it spans $110+110 = 220$ cents, or 215 from the equivalent notes on the higher pipe, reasonably close to the theoretically required 204.

The right-hand pipe replicates a large part of the same structure but omits the middle note of the higher *pyknón*. In this way, that *pyknón* is now reinterpreted the other way round, as a disjunctive tone, where the other pipe had two tetrachords in immediate succession. The upper *pyknón* of the higher pipe thus starts where that of the lower pipe ended, resulting in four successive “semitones.”⁷⁵ Unimpeded by the structural restraints that forced its lower companions into conforming with a “tonic chromatic,” the highest *pyknón* is free to implement a tenser variant of about $151+133 = 284$ cents, comparable with the chromatic divisions underlying instrument W1, calculated as 254, 263, and 274 cents (fig. 7.30). The exact size of this high *pyknón* is chosen so that its top note can also complement the high tetrachord on the lower pipe, standing a fourth above the bottom note of its *pyknón*.

All in all, we seem to observe a chromatic variation on a theme that we once more know from Ptolemy. In principle, musicians prefer a noncommensurable tetrachord division: “tonic diatonic” in Ptolemy’s tunings, and tense chromatic on the present auloi. However, where required by structural analysis, this division gives way to a more traditional commensurable set of intervals: respectively, “two-tone” diatonic and “tonic chromatic.”

Unlike W1, this aulos therefore implements a kind of modulation between two neighboring keys, which are neatly distributed between the pipes. Being realized by switching between a “conjunct” and a “disjunct” upper tetrachord, realized respectively on the lower and higher pipes, this kind of modulation enjoyed a special status in Greek theory. Instead of subsuming it with all other modulations along the circle of fifths as a “modulation by key” (*metabolē katà tónon*), it was called “modulation by scale” (*metabolē katà sýstēma*).⁷⁶ Accordingly, the most comprehensive version of the model two-octave “Perfect System” joined both options to an entity that remained canonical until the end of antiquity. Modulation of this special kind was common enough to spawn technical language: “‘circular’ [melody] is the kind that includes modulation, such as when somebody after ascending through a tetrachord in conjunction then descends through it in disjunction”⁷⁷—a definition that almost reads like taken from a manual for instrument W2.

74. A “Hypodorian” tuning, *trópoi* retains the upper tetrachord of the “natural” tuning. See Ptolemy, *Harmonics* 2.16, p. 80.15–16 Düring; see, e.g., West 1992: 171; Hagel 2009a: 196.

75. For an analysis of modulating structures resulting in originally “forbidden” tonalities, see Hagel 2000: 38–80.

76. See, e.g., Cleonides 13, p. 205.5–10 Jan.

77. Aristides Quintilianus 1.9, p. 16.24–17.2 Winnintgon-Ingram: περιφερῆς δὲ ἡ ἐμμετάβολος, οἷον εἴ τις κατὰ συναφῆν τετράχορδον ἐπιτείνας ταῦτὸν ἀνείη κατὰ διάζευξιν.

The teardrop hole, in contrast, would enable switching from the chromatic genus to the much smaller *pyknón* of enharmonic, enabling, in ancient terms, a “modulation by genus” (*metabolê katà génos*). This makes the present instrument a crucial witness to the survival of true enharmonic into the late Hellenistic period.

On this aulos, as well, any attempt to associate its pitch with a particular ancient key may be futile. If one wanted to pin it down, the scale of choice might be the Hyperphrygian, the pitch of whose *mésē* Γ (*c*) closely coincides with the instrument’s functional *mésē*, that is, the pivotal note from which the scale bifurcates upward. Interestingly, the best fit overall is achieved at a reference pitch of approximately 497 Hz, which is identical with the pitch of the instruments with mechanism discussed above. However, it is difficult to understand why one of these two auloi of similar make would have realized a key in the old Phrygian family, transcribed with three flats, while the other would rather fit a late one, transcribed with four sharps.

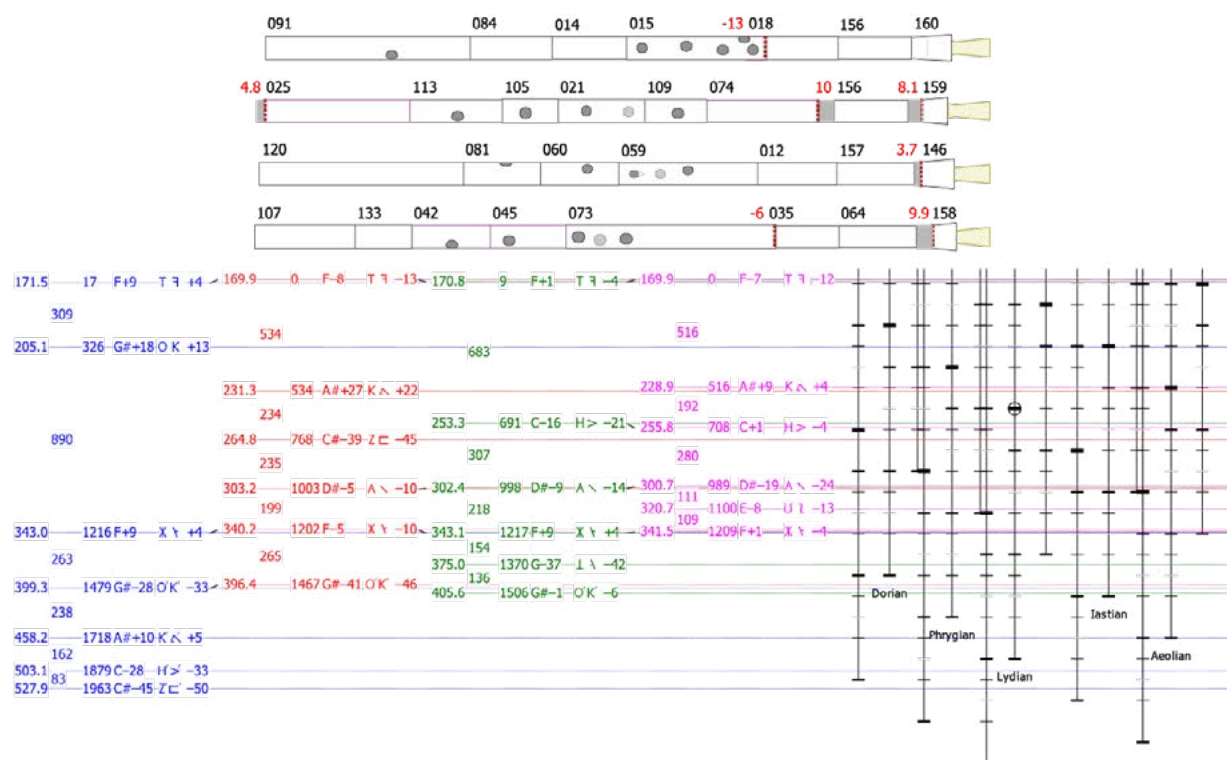


Figure 7.34: Optimized pitches and intervals for the full set of W1-H, W1-L, W2-H (reed: 23.4 mm), and W2-L. Holes below: open; thumbholes closed; teardrop-hole: edge covered; lateral hole: partially covered; Lydian *hyperbolaía*: 483Hz (490Hz – 25 cents); harmony: 81/4/2/3/5 (threshold 20 cents).

7.1.3.3. Playing Together?

Getting W1 to perform in Hyperphrygian, at any rate, appears impossible—with the longer reeds required to play at that pitch, the intervals would be desperately out of tune. Does this mean that W1 and W2, even though they might conceivably adhere to the same standard pitch, were hardly meant to play together, even though they are similar in design, in overall length, as well as in their chromatic tonality, which all set them apart from all other aulos finds?

In fact, a reasonable overall harmonicity may be achieved by adjusting the effective reed lengths of the two instruments in opposite direction, slightly out of the individually predicted optima.⁷⁸ This brings the double instrument closer to the “Hyperaeolian” interpretation, with all its inherent troubles (fig. 7.34).

78. Note that only W2-H preserves the precise extent of tubing above the toneholes, while the other three pipes are all broken in ways that merely allow establishing a minimal length (and therefore a maximal effective reed length for a given overall effective length). A reconstruction would reasonably aim at four reeds of similar length.

The top *pyknón* of W2-L thus stands a fifth below that on W1-H, forming the conjunct alternative to the latter's scale, while the top *pyknón* of W2-H, only a fourth below, provides the regular option. A melodic movement on the treble notes of W1 could thus be paralleled either a fourth or a fifth lower on W2, thus associating it with either of two neighboring scales.

A joint performance of the two instruments therefore appears still possible, perhaps even likely. It would underline the chromatic nature of their music and develop the protean capability for modulation further.

7.1.4. Reed-Socket Cones

Most of the uppermost parts of the pipes are highly fragmented, since their lower ends consisted of a thin metal cylinder over even thinner bone, while their conical upper ends break easily due to the wide internal bore that received the reed. Nonetheless remains of all eight small reed-socket cones could be established. In spite of their general similarity, their diameters and the dimensions of various features are distinct enough to sort them into four pairs: thus 146 would belong with 158; 159, with 161; bone part 055 within metal encasing 223, with 160; so that 110 is left to go with 038. These four pairs may be assigned to the four shorter and slenderer instruments on the basis of, first, the diameters of the bore and the socket of the cone which must fit closely over the spigot extending from the proximal side of the bulb, and second, by the ways in which parts of these spigots either are still part of the bulbs or broke off and are now partly stuck in a cone. Most probably, S1 thus sported 038 and 100; S2, 160 and 055/223 (making it the most complete instrument also for purposes of exhibition); W1, 161 and 159; and W2, 146 and 158.

All this helps little for the interpretation of the instruments in terms of the actual lengths by which the reeds extended from their sockets. Of all the cone sections, only 160 and 223 preserve their total lengths, so that we cannot know whether differences in total effective length were partially covered by cones of different sizes. To be sure, since the actual reeds anyway butted against the spigot of the bulb, this is a purely aesthetical question without any bearing on the musical interpretation.

The overall construction of a cone with cylindrical “foot” forming a delicate socket that went over a spigot, together with the fact that hardly any of these spigots had actually remained within their sockets and thus protected them, suggests that the pieces had not been permanently glued, but secured only by a thin layer of thread, keeping them movable against each other.⁷⁹ In this way, the reed could be easily adjusted without jeopardizing air tightness.⁸⁰ On the one hand, it was thus possible to turn the reed blades to the most comfortable orientation for a given fingering when the hand position moved along the pipe on the modulating instrument. On the other, it became possible to tune the instrument by changing its effective length by a few millimeters. The effect would have been enhanced by the increased bore diameter within the gap that was opening up between the end of the bulb spigot and the end of the reed, potentially adding another motive for making the socket walls of the cone foot as thin as possible.

7.2. The Long Pipes

7.2.1. Reconstruction

The final set of structurally comparable instruments also consists of four pipes, as indicated by four large bulbs as well as the remains of four slider mechanisms ending in tiny dolphins with shells in their snouts. In contrast, there are only three “chimneys,” short oblique tubes soldered over particular fingerholes—a number that would inevitably break symmetry in some way. Being by far the most thick-walled objects, the loss of an entire chimney to processes of corrosion and squashing can safely be excluded, nor would it have been a likely object to be overlooked by the excavators.

79. The incisions running around the spigots on 111 and 134 would then serve to hold the windings in place, not to ensure a better grip of the glue, as must have been the purpose of similar incisions beneath bronze encasings.

80. See Hagel 2012a.

Even a cursory overview of the over fifty sections of comparably large diameter gives an idea how long these instruments must have been. Indeed, it took us a while to accept that all these parts indeed belong together. This insight was not least hampered by the fact that the internal diameters may here vary throughout an instrument, while it had generally been accepted wisdom that an aulos pipe was simply cylindrical, minor deviations being attributed to taphonomy or negligible imperfections of workmanship. In addition, we had to acknowledge, for the first time, that wood and bone cores could alternate along a single pipe (only later we saw that the same was true for the slender pipes with mechanism). While sections with rotary sleeves seem almost always built around bone, all other parts of an instrument might as well include wood instead. This was not only considerably cheaper, bone of the right diameters being a limited resource with only a few usable inches coming from one animal, but also made for lighter instruments, weight being a decisive factor in pipes of such a size, which still needed to be simultaneously supported and manipulated each by only one hand. Even though some of the wood is preserved, it has of course shrunk and warped. As a consequence, it is once more impossible to establish the original internal diameters for large parts of the instruments, which in turn affects the precision of a musical modeling. In many places I have therefore been forced to interpolate between known diameters.

When working with the material, the slowly consolidating stretches of tubing emerged mostly to belong to three types of constituent parts: tops, tails, and, separating these, slider compounds. The hardest problem concerns how to put these together to form complete pipes. Since the space within which the objects were buried was not large enough for such enormous instruments, the pipes needed to be broken before burial, each at least into three parts. As a result, some important places have suffered partially irretrievable damage, which is most disconcerting in the cases of some holes that had been covered by the dolphin sliders: consisting only of a single thin metal sheet on wood, two of the respective sections are now fractured beyond much hope.

Otherwise the slider compounds consisted of a comparatively long and sturdy tube, between 13 cm and 26.5 cm in length, on which the slider rods were mounted, with the help of at least two delicate “guides” that were soldered to the tube surface (see fig. 5.6).⁸¹ Since the rods consist of two parts connected by a semicircular bracket going halfway round the tube, and the guides are distributed above and below that bracket on opposite sides, they do not only hold the slider in place but at the same time also restrict its longitudinal movement to precisely the diameter of the hole. In this way, the combination of at least the lower part of the slider, from the shell to the bracket, in combination with the soldering trace of at least one slider guide allows to pinpoint the hole position in relation to the tube with precision. Where the upper, longer, part of the slider is also preserved, we can also predict the precise range where the knob at its end moved. As is to be expected, this region lies always within the range of the fingerholes, well beyond the tube on which the slider was actually fastened.

Tails come in two different kinds. On the one hand, we have two long metal tubes (049 and 092), measuring more than 27 cm, without any holes but terminating in bells. As these are completely empty, they must have contained a wooden core, after whose decay the tubes have partially collapsed, to be restored only thanks to Susanne Gänsicke’s keen eye. On the other hand, the in situ photographs allowed us to reestablish two long rows of sections with fingerholes and rotating sleeves (compounds 001–095–071–099 and 087–096–098–009–041). The distance between the holes in question clearly assigned them to the bass region, playing notes between 80–100 Hz, about modern E_2 – G_2 . That they were outside the reach of the player’s hand is also shown by the fact that their holes are freely distributed on various sides of the tube. Furthermore, they include large rectangular openings which a human finger could not possibly cover. A few more loose sections appear to belong in the same category, but cannot be located on the photographs.

The tops, finally, contain the fingered parts. In contrast to all other known auloi that feature sleeve mechanisms, the topmost holes are here not equipped with any; so much is clear from four pieces with

81. These guides rest on outward-bent “feet” that were soldered to the tube. The feet come in two varieties, a plain rectangular and a fancier one. An example of the latter is still attached to tube 050, while clear traces of another are found on 036. However, since two more of that type remain, the shape cannot contribute to the question of how the pipes were paired.



Figure 7.35: The spigot of bulb 137 (left) within the fragments of tube 063.

sleeveless thumbholes, one for each pipe. All in all, 18 holes without sleeves are at least partially preserved (not counting tiny hole fragments in the remaining assortment of unassigned fragments, which may belong to extant broken parts). Of these, four need to be reserved for the dolphins. Fourteen holes may give seven per pair and thus three or four for each pipe—as turns out to be the case. There are two tubes, 063 and 128, with very similar arrangements of index, thumb and middle–finger holes, the upper two widely spaced, the lower much more closely together. Tube 063 extends 12 cm upward from the index hole, leaving hardly any room for a spacer section between itself and the bulb. In fact, it was found with the spigot of bulb 137 still in place (fig. 7.35). With a reed cone such as 118, it would optimally have played either the notes K — I — Z , or alternatively I — Θ — E , a semitone higher. The first would be part of the Hyperiastian scale, which was common in the Roman–Imperial period, the latter point to Phrygian, found in earlier musical documents. Much the same is true for 128, with the sole difference that its semitone is somewhat larger. In short, from a first impression, since they fit within the same pitch range, they should rather belong to similar pipes from different instruments than to the same pair. This appears confirmed by spacer tube 017, which complements the upper part of 128 to the extent of 063.

However, there is an important difference: the thumbholes of the two sections are distinctly displaced in opposite directions; so are the index holes, as is necessary when managing huge finger spans. Were these two similar pipes, but belonging to opposite hands?

Further thumbholes are found on 034 and 039, which also contain the corresponding index–finger holes. The two holes on 039 are however more closely spaced. In both pieces, the thumbhole is formed in teardrop shape, with the corners pointing upward, as expected. However, the two teardrops are mirrored, and so is the displacement between thumb and index holes. As a brief experiment clarifies, a teardrop hole of this sort is conveniently fingered when its tip points away from the player’s hand; taken in the wrong hand, it is most cumbersome to seal and much more difficult to release. Part 039 must therefore belong to the right hand and 034 to the left.

The last remaining item with two holes, which assign it to the fingered region as opposed to the dolphin holes that must be solitary, is 089. The distance between its holes is extremely wide, requiring a formidable finger span of 7 cm. Moreover, the two holes are shifted by 90 degrees, and one of them carries soldering traces that can unambiguously be assigned to “chimney” 090. A tilted chimney like the three in the Meroë find can only serve a single purpose: physically displacing the musically required hole position to another point a bit further up the tube, where it could more easily be reached. This is achieved by effectively increasing the wall thickness of the instrument at this place, so that the total length from mouthpiece to the surface of the finger hole becomes larger.⁸² The chimney is functional only when tilting upward, toward the finger that is just able to reach its top, but not the place a couple of centimeters below where a hole playing the same pitch without a chimney would come to lie. In this way, the orientation of the piece can be deduced from the orientation of the chimney. On 090, the chimney thus belongs to the higher of the two holes, while the lower fingerhole points almost directly left when the chimney looks straight upward. This, therefore, is also a left-hand section. Placing it below

82. The effective increase in “wall thickness” is given by the length of the chimney’s bore at its center. It can be conveniently calculated from the height of the lower edge of the chimney exit above the tube wall (h_0), which is expediently measured with a caliper, the angle of the chimney (α), and the diameter of its bore (d): $\Delta l = \frac{h_0}{\sin \alpha} + \frac{d}{2 \tan \alpha}$. We obtain, for 065, 15.5 mm; for 090, 14.0 mm; for 149, 11.2 mm.

028 with its three holes is out of the question: while the span between the upper rim of the index and the lower of the little-finger hole, amounting to 18.5 cm, might be just possible as such, it is definitely unfeasible when the other holes also need to be covered. Therefore, 089 must go below 034. In this way, the chimney is assigned to the middle finger (which indeed could not possibly reach the position those about 19 mm further down that the chimney makes good), and the lower hole to the little finger. The ring finger remains free, for the moment, and comes to lie just below the chimney's rectangular foot.

Similarly, two holes without sleeves remain for the other pipe. They are easily told from possible dolphin holes because they both show traces of solder, which are dissimilar enough to be associated with the remaining two chimneys: tube 131 once bore chimney 065, and tube 100, the much smaller 149. The latter section must have been the lower because old photographs show it attached to section 082–086, a piece with two toneholes, the lower of them rectangular; as is best visible on the x-ray images, the upper part of 086 forms the connection of two-layered metal with bone core to the simple metal encasing fitting the wooden core of the upper part of the instrument. Item 131 has suffered considerable damage; of its downstream rim, only the underside half remains intact. The same is true for the upstream rim of 100 (fig. 7.36). Remnants of a very thin metal ring are discernable that was soldered inside the lower end of 131 and had extended beyond it, apparently to secure the alignment of the sections (fig. 7.37). When the fractures are aligned, the holes show the same azimuthal displacement as do those in 089, only in the opposite direction, the little-finger hole pointing rightwards: these pieces evidently belong to a right-hand pipe.

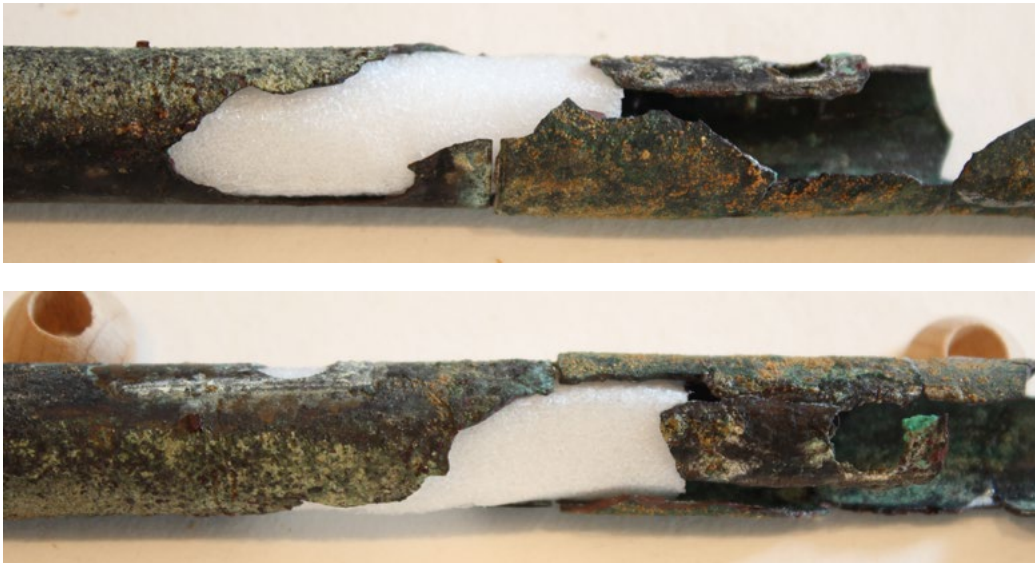


Figure 7.36: Aligning parts 100 and 131. Note the chimney solder traces around both holes.

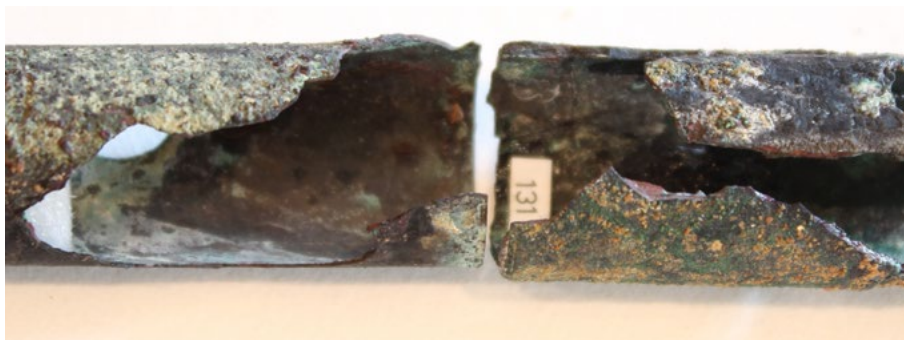


Figure 7.37: Remnants of a thin ring internally connecting 100 and 131.

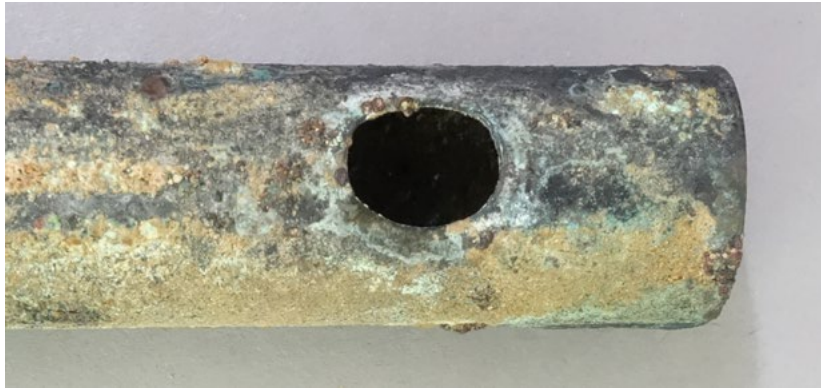


Figure 7.38: Likely traces of a lost structure modifying the lower hole of 089.

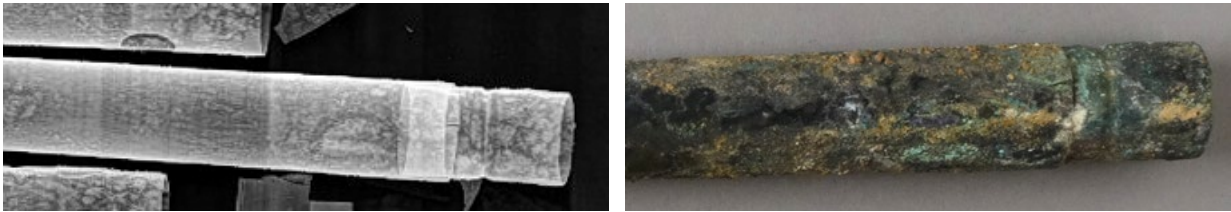


Figure 7.39: The end of 085 with inserted tube with groove.

The hole of 100 is however placed about 14 mm further up relative to its upper neighbor. At a first glance, its chimney more than compensates for that difference: the interval between the hole pairs appears about 20 cents larger on 100+131 than on 089, as long as the adjacent lower hole, on 086, is open. But this cannot have been the most typical state of that hole, because an open hole between the fingers and the slider hole renders the slider mechanism useless (we will come back to this consideration). When it is closed, the difference between the respective intervals rises to about 40 cents, which is far from negligible. Does that divergence of nearly a quartertone reflect a functional difference? We will see below, that this is unlikely for musical reasons. At present, we may additionally point out that the presumable little-finger hole in 089 is not only extremely far removed but also apparently larger than any other fingerhole in the entire set (not counting the teardrop-shaped elongations on two thumbholes)—a combination that must encumber efficient sealing by the smallest finger. After all, a smaller hole a bit further up would have improved ergonomics on both counts while still playing the same pitch. Or was a fourth chimney lost at this place, as the analogous structure of 100+131 with their two chimneys might suggest? Whitish traces and linear features around the hole appear to intimate that something had been soldered there (fig. 7.38). However, the lost structure would appear significantly smaller than the base plates of the extant chimneys, suggesting a much less protruding attachment, in line with the required small pitch correction. Without the hypothetical part, we cannot do any better than guessing its properties from that “required” correction, assuming the interval was functionally similar on the two pipes. Judging from the three chimneys, we would assume that the outlet was smaller than the hole in the bronze tube, which might already account for a substantial part of the expected pitch adjustment. For the rest, a small elevation would suffice, perhaps more inclining the opening toward the player than overall removing it from the surface of the tube, so that it becomes more readily accessible to the tip of the little finger. The relation of the two factors is difficult to guess. If the effective area of the hole was reduced by half a millimeter in every direction, for instance, the interval in question would approach that on the other pipe at an average elevation of 3.7 mm. At any rate, in the following we will tentatively assume that the two intervals were similar.

The fingered regions of the pipes, great parts of which we have thus established, are below continued by the parts bearing the sliders. Of the respective sections, 085 is by far the longest. It is extraordinary also in another respect. Into one of its ends, another, short metal tube is fitted, inserted by about 8 mm, protruding 18.8 mm, and featuring a rounded groove at the outside, 13.7 mm from its end (fig. 7.39). This

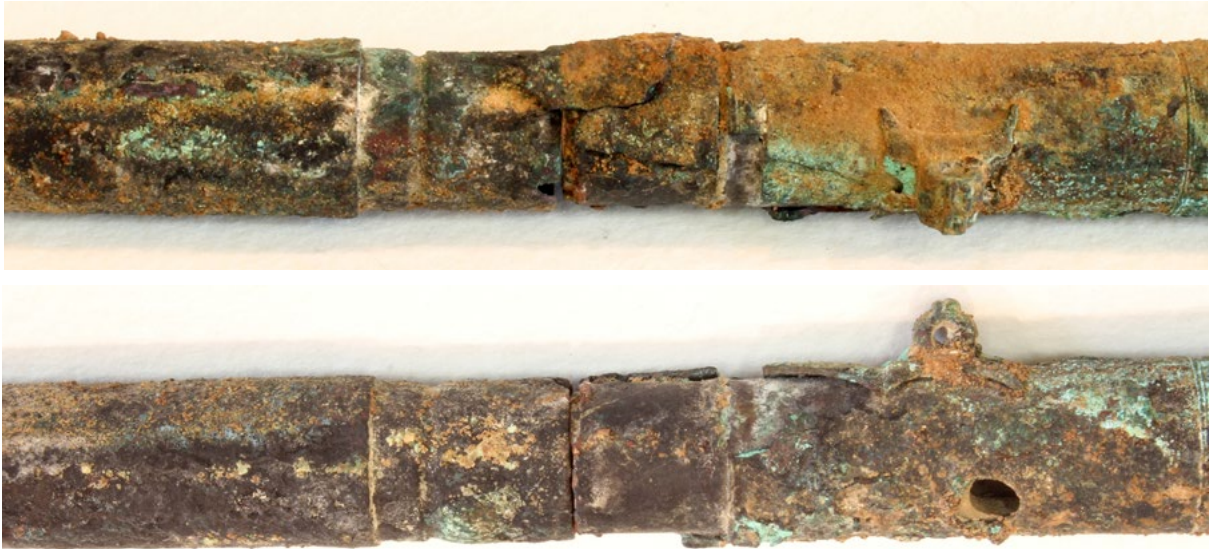


Figure 7.40: Joining parts 085 and 072.

groove is just 1 mm wide and was worked into the tube in a way that makes it also clearly perceptible at the inside of the tube. If it was created only after a wooden core had been fitted, it would have held that core securely in place. Only a few fragments remain from an outer metal shell that once covered the protruding tube and must have connected it with the neighboring section. This was apparently 072, which is similarly unique, sporting a fingerhole with a wide sleeve and a ring-shaped knob, the only one out of five that is still in place, in between two spacer sections. One of these is inconspicuous, consisting of an external shell over the inner encasing, both with the typical thin walls. On the other side, however, we find an exceptionally thick inner wall with fragments of an outer sleeve, partially still protruding beyond the confines of the piece. The inner “spigot” is identical in diameter with that protruding from 085, so that the external sleeve would have been able to connect these firmly (fig. 7.40).

Since having a revolving sleeve mechanism on a slider hole would hardly make any sense, 072 must have been placed above 085, not below it, which clarifies the orientation of both. The two sections must have been fitted with one of the two broken slider rods, 052 or 053, to one of which the detached slider knob 051 must once have belonged as well. From the lower end of the latter, about 25 mm have been lost since the excavation (fig. 7.41). From the missing upper end, at least the knob may still have been preserved during the excavation (fig. 7.42). The brackets of both 052 and 053 went clockwise around the tube, when viewed from the player’s perspective. Unfortunately, if the tube preserves traces of its bracket, these can hardly be told from products of wishful imagination.

The second longest slider tube is 032. Here the relative positions of the operated hole and the range across which the knob moved can be determined with precision since all relevant parts are preserved, with the upper part of the dolphin–slider rod (054) still corroded to a fragment of the tube, as is part of the bracket, the end of which broke away with the long part of the rod leading to the knob (117); even traces of the guides are beautifully preserved on both the tube and the rod.⁸³ From the tip of the shell to the end of the knob the construction measures about 336–338 mm. The bracket goes counterclockwise around the tube.

The construction of 050 is very similar. The fundamental parameter, the total distance between hole and operating finger is practically the same (about 335.5 mm, which now need to be measured along a bent rod), and the bracket is also oriented counterclockwise and sits at the same distance from the

83. About halfway between dolphin and bracket, what appears to be the upper “bar” of an actual slider guide is found corroded to the top of the slider. It cannot originally have belonged at this place, because no other slider has a guide at this place and the solder traces of the guide are clearly visible at the accustomed location, directly at the lower end of the bracket’s moving range. Probably the guide had been torn off the slider tube and moved downward a couple of centimeters along the rod which it enclosed on three sides when the pipe was fractured.



Figure 7.41: Loss of material from item 051 between the excavation and the present state. Bottom: position of 051 as a direct continuation of 052 on 007+085 (probably too short).

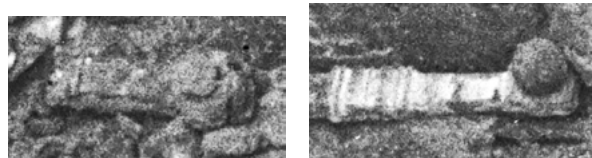


Figure 7.42: Probably a lost slider button (230, left); for comparison, the corresponding part of 051 (right).

shell end, but a millimeter higher on the tube. However, the tube is 8.5 cm shorter, indicating that the remaining length may have been used differently on the respective pipe.

Finally there is 036, of the same length as 050 but belonging to a clockwise rod. It exhibits solder traces from both guides, so that a precise hole position may be retrieved for whatever dolphin slider can be assigned to it.

Of the four extant sections or section fragments with potential dolphin holes, only 029 and 007 have both ends preserved, 227, only one end, and 200, none at all. Furthermore, 029 was in situ connected to 097 and 094, two sections with each one rectangular tonehole, which clarifies the direction of 029 (fig. 7.43). The orientation of 007 is also clear: First, its hole is so far removed from one end that none of the dolphins could reach it that way, and second, its dolphin left tiny but unmistakable gray traces of body and lateral fins right next to the hole, which may result from the tinned underside of the slider (fig. 7.44).

Disappointingly, none of the two preserved and the two possible dolphin positions aligns with any of the presumed dolphin holes when the pieces are directly connected, depriving us of a powerful criterion for the connection between tail and center parts. However, solutions for the two certain dolphin positions can be found using short spacer parts. In particular, 050 fits with 227 via 150, and 029 with 032 via 061 (fig. 7.45). The latter may appear surprising because it introduces a fingerhole with mechanism right above the dolphin hole. But there is nothing a priori alarming in such a configuration. After all, we



Figure 7.43: Parts 094+097+029 when excavated and after restoring.



Figure 7.44: Dolphin traces on part 007.



Figure 7.45: Parts 029+061+032.

have seen that such a hole was set above the slider tube 085, and the same must have been the case for the above-mentioned two toneholes in 086, right below the chimney holes. The special status of 061 is confirmed by its unique shortness, which might make it look like a component of the slender pipes, were it not for its diameter. Cramped in between the bracket region on the slider tube above and the slider hole below, its exceptional size appears well motivated. It contains no bone core, which is true only for a minority of pieces with sleeve mechanism, which may corroborate the idea of placing it between two longer sections that had clearly had wooden cores.⁸⁴

The most important clue to the original location of the sliders is of course their ergonomics. With all the other sleeve-operated bass holes, which needed to be set in advance and could not be changed during performance, it is obvious that the dolphins would in contrast move back and forth during playing—otherwise just another rotary sleeve would have fulfilled the same purpose with much less effort. The knobs must therefore be placed close to the tip of a finger that was at liberty to operate them. Since we have found that on the two pipes with chimneys the ring fingers were left unemployed, this is doubtless

84. The orientation of 061 is difficult to establish but does not affect the analysis. Similarly, the absence of certain knob traces encumber assessing the direction in which the hole was turned; most probably, it faced about 90° toward the right, starting from the upper part of the slider.

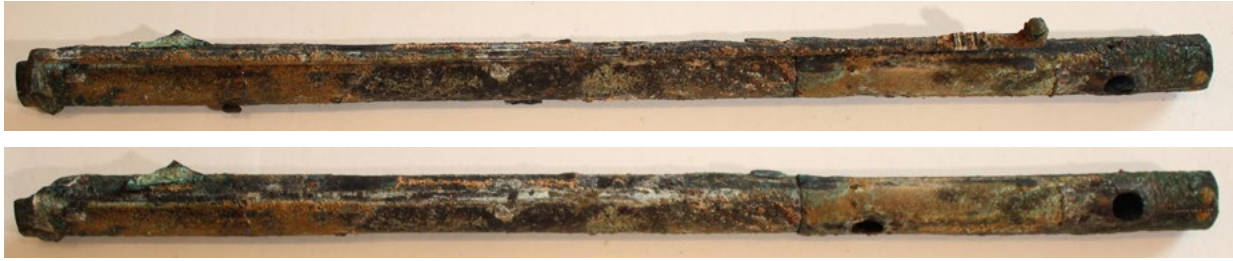


Figure 7.46: Parts 032+089 with slider-guide solder traces left and center on 032.

the first place to look. The extremely long 085 is no plausible candidate for these pipes because the combined lengths of 052+051 would not reach anywhere close to the ring-finger position. In contrast, 032 and 050 work perfectly. First, their difference in tube length (82 mm) makes up for the extra piece 086 (87.5 mm) that was attached to 100. Second, when 032 is placed below 089 (fig. 7.46), the slider knob abuts against the foot of the latter's chimney when the rod is fully pulled up and the dolphin hole becomes fully open. Presumably, the chimney foot thus served as an additional means of physically restricting slider movement, thus ensuring that the soldered slider guide right above the bracket far below was not inadvertently ripped off (fig. 7.47).

Third, the corrosion patterns on the tubes align, including a line of possible white tin and blackish corrosion that runs up to the right side of the chimney foot, ending in a small black rectangle that matches the position and shape of the rectangular end of the rod on which the globular knob is placed (compare fig. 7.47 with similar traces, apparently left by a dolphin, in fig. 7.48).⁸⁵ The corresponding surfaces on 086 and 100 cannot be expected to show direct traces of the rod, which had been violently bent away from the tube, right starting from the bracket. But here, as well, the upper end of the rod of 050 would have met with the foot of the chimney as soon as the hole was fully open.⁸⁶ This may appear too good a coincidence to leave any doubts about the arrangement; however, we will see below that the association of 050 with 086+100+131 creates problems on another front. Might the perfect fit of 050 only reflect the similar construction of 036? These two slider tubes are not only of identical length (measured as 132.0 mm and 130.7 mm, respectively), but may also have shared similar downward extensions of their associated slider plates (established, in shut state, as 53.05 mm versus 53.9 mm, when 036 is associated with dolphin 053), and the similarity in construction is underlined by the likely presence of a short spacer between slider tube and slider-hole section (150 of 20.25 mm versus 127 of 18.9 mm length). Thus, we cannot a priori exclude the possibility that the upward extension of the two associated slider rods was also similar, so that 050 only reflects a correspondence that had been functional on 036. In short, a fit within a couple of millimeters would have been warranted if the total slider on 036 was not much more different in length to that on 050 as we have seen was that on 032. On the other hand, while the construction of the rod of 032, as we have also seen, resembles that of 050 very closely, this is not similarly true for either of the fragments that might belong on 036: on both 052 and 053, the distance between dolphin and bracket is about 4 mm larger. Therefore, it seems more probable that the instruments were equipped with two different slider designs, one clockwise and one counterclockwise. In this case, there is no reason why two internally different designs should be of exactly the same overall length, especially since they must have served different purposes. On balance, it is more than likely that 050 indeed belonged below 086+100.

The longest slider tube, 085, along with its attached fingerhole section above, 072, must then belong to one of the three-holed fingered sections, 028 or 063, and presumably directly below it, in order to keep the rod in the reach of some finger. Being so similar apart from their handedness, the two will be

85. The black rectangular traces end 5.6 mm below the chimney foot; the position of the slider, judging from the space between bracket and upper slider-guide traces, is 5.3 mm below fully open. The black corrosion, slightly raised above the surrounding greenish region may have been caused by the original contact with a tinned surface.

86. This slider was buried in a position 1.5 mm below fully open. Note that the combination 227+150+050 creates precisely the corresponding 1.5 mm overlap between the dolphin shell and the hole it is meant to cover.



Figure 747: Part 089 with chimney and slider knob (in partly open state).



Figure 748: Probable raised corrosion “shadow” of dolphin 053 on tube 085.



Figure 749: Potential traces of the slider bracket on tube 085.



Figure 750: Aligning parts 036–121–077–076–006.

difficult to associate with a particular lower part. Since 072 features a sleeve whose knob is placed at the right side, one might argue that placing it on the right-hand pipe, that is, below 063, would secure the additional option of working the sleeve during playing. But the knob sits some millimeters further down the tube: if it was meant to be used during performance, would it not rather be placed closer to the hand than further away?

The details of fingering depend on the original length of the slider, which we unfortunately do not know. If it was just as long as the extant ones, it would have reached right to the edge of the fingerhole, so that the little finger could either play on the hole or, when it was closed by its sleeve, work the slider. But this would leave the ring finger unemployed. A shorter slider might still have been accessible to the little finger, while leaving the hole to the ring finger; but the ensuing span must have been extraordinarily taxing. More probably, the slider would have been even longer, to be more comfortably accessible to the ring finger, while the little finger could play on the hole. After all, the sliders on the pipes with chimneys were also assigned to the ring fingers.

Which slider belongs here? The corrosion on the tube makes it impossible to tell. The best candidates for traces potentially associated with previous slider guide locations would nicely fit for the dolphin part 053, in combination with 007; in contrast, the best candidates for bracket marks, highly doubtful as well, suggest the slightly longer 052 (fig. 7.49). At any rate, the coinciding lengths of the sliders on the other pipes might impart some confidence in taking the existing parts as a reasonable guide here as well, regardless of which specific dolphin was originally attached to the piece.

The other pipe then included the much shorter slider tube 036. The position of the dolphin hole below it is readily established on the basis of the measurements of either 052 or 053. With the latter, it would be about 4 mm lower, with relatively small musical consequences, at a region that far down the instrument. In analogy to the established connections, we may expect that the gap left by the shorter tube was filled with toneholes with sleeves. Indeed, the remaining assortment of four single sections with round toneholes that are too short to provide combinations spanning semitones in the bass region below the sliders fills exactly the required space. Their arrangement follows almost automatically from bone cores, breakage and corrosion patterns: it must have been 006–076–077–121, with a total of five toneholes (fig. 7.50).

The first piece in this series (006) has had its external layer restored from thickly corroded splinters, resulting in an unrealistic wide diameter that prevents a convincing joint to its outer neighbor. From the end of the last piece, 121, a few dents of very thin metal remain protruding—apparently once more a



Figure 7.51: Parts 039 and 102.



Figure 7.52: Potential traces of a slider knob plate on part 006.



Figure 7.53: Item 033, a bronze encasing apparently folding over the left edge of a lost wooden core, during excavation.

token of joining to a single-layer section. If this end is attached to the slider tube (036) and the other to the piece with the three top finger holes, the three central holes of the five can roughly replicate two or, using cross fingering, three pitches from the other pipe with fingerholes in that region (086+100 above slider tube 050). The holes in question become musically aligned, if the latter pipe is granted an upward extension that brings only its top two fingerholes above the index hole on 028. Among the remaining spacers, only 102 would contribute the required length; it also fits perfectly (fig. 7.51). In addition, one of those holes may align with that in 072 as well. It is not the top hole but the second in the series, suggesting that the hole in 072 was also played by the little finger.

This would agree with potential traces of a slider button plate on 006 (fig. 7.52) that, if identified correctly, reach up to the ring-finger area, where 072 has no hole, so that an analogous slider there would explain the lack of a ring-finger hole on this piece. In addition, the position of the slider relative to the hole would assign 006 to the right hand and consequently join it to 063. If 17 mm are restored to the broken lower end of the latter, 006–063 can play the same pitches as 072–028–017. As we will see below, the ensuing length difference of half a centimeter between the upper ends of these sections is offset by the different lengths of the bulbs that must have belonged to each.⁸⁷

87. 028+117+136: 118.7 + 89 + 64.5 = 272.2 mm; 063+137: 17 + 183.5 + 70 = 270.5 mm.

Unfortunately, potential symmetries are broken regarding the knob positions: just as on 072, those on 006 also point to the right side of the pipe, although the two pipes in question must have belonged to different hands. Knob direction as such can therefore not serve as an indicator of handedness. At least, in contrast to 072, the knobs on 006 are not placed further down than the corresponding holes, so that they might have been operable by the right hand during performance.

Finally we need to address the parts below the slider holes. Here it becomes immediately clear that no balanced design might be achieved by combining the long tubes with bells (049, 092) with the established longer sequences of toneholes (compounds 001–095–071–099 and 087–096–098–009–041): these must have been alternative options. Judging from the hole distances, the latter two must have sat at overlapping regions. They can be extended to the same overall position by adding compound 005–024 below 001, and item 026 below 087, followed by 033, a piece that is now broken, but whose length can be established from an in situ image. There, the bronze encasing appears to fold over its edge, suggesting that the part terminated the tube (fig. 7.53).

In this way, both ends obtain another tonehole. The resulting segments have practically the same length and a matching series of five holes each. The basic difference is that 005–024+001–095–071–099 have their two lowest holes round, but 026+087–096–098–009–041, rectangular—and, incidentally, that the end of 041 sports a massive spigot of exposed bone. Since ancient music knew of no extended sequence of roughly similar intervals other than semitones,⁸⁸ the two tonehole arrays are long enough to assign them to a particular tonal range with some precision, which in turn locates them at a specific distance from the upper ends of the instruments. The exits must have played a pitch of about 70 Hz. In this way, the distance of these long end sections from any of the established upper parts becomes too small to accommodate either of the remaining longer segments, 047+046 and 003–010. These must therefore go somewhere above the two long bell sections without fingerholes, which may originally have been of precisely the same length (049 is now 2 mm shorter than the complete 092 but has lost its upper edge). Indeed, inside 047 the bone lining switched to wood.⁸⁹ The resulting two “tails” with long end pieces and only a few, round toneholes thus become even longer than the two with many toneholes some of which are rectangular. Assuming not completely dissimilar total lengths of all pipes as well as reasonable offsets between the fingerhole regions, ranging between one and three holes as on all other known auloi—above we found an offset of two holes establishing matching pitches—the two shorter ends, with many holes, must be assigned to those pipes whose central parts extend further downward. Thus they were once attached to 007 and 094, respectively. Which of the two went where may be impossible to establish with ultimate certainty, but hardly matters musically. Either would require a short spacer if placed below 007, for which item 142 suits well. If 041 is placed here, its long spigot would extend through the spacer into the dolphin-hole section. Such a connection is however discouraged by the wood fragments in 007: if these belong together the way they seem, the wooden core would have extended throughout the section so that it could not have accommodated the spigot of 041. Below 094, the spacer fragment 206 appears ideal; it would here cover the spigot of 041 completely. Eventually, the evaluation of possible pitch configurations will also suggest joining 041 rather with 094 for the sake of a slightly better harmonic balance. Also, the predilection for rectangular openings in 026+087–096–098–009–041 as opposed to the more frequent round holes in 005–024+001–095–071–099 may speak in favor of placing the former below two further rectangular holes, in 094–097.

Regarding the other two pipes, the shorter of the remaining pieces, comprising 047+046, must be assigned to the longer slider section, the one with slider tube 036. Unfortunately, their original distance cannot be physically established because the intervening piece with the slider hole is largely destroyed. We encounter the same problem with 003–010 with its three holes and a protruding bone end, which comes to sit below slider tube 050, from which it was separated by a dolphin-hole section of which 227

88. While no more than two subsequent semitones can be part of an individual ancient scale, the arrangement of the various keys along the circle of the fifths created an uninterrupted sequence of semitones; see, e.g., Aristides Quintilianus 1.10, p. 21.4–5 Winnington-Ingram: ἕκαστος δ' ἂν αὐτῶν ἡμιτονίῳ μὲν ὑπερέξει τοῦ προτέρου “each of them will lie a semitone above the preceding.”

89. See Bodley 1946: 228–29.

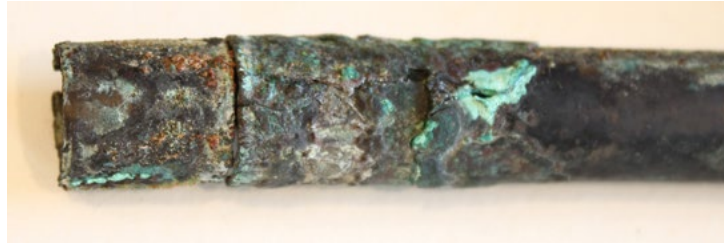


Figure 7.54: Parts 027 and 036.

(including half the hole) and possibly 209 form the shattered remains. Since the difference between the relative dolphin-hole positions, always judging from probably aligning holes on the upper ends, appears larger than the length difference between 003–010 and 047+046, it is more likely that the last remaining section with a tonehole, 022, belongs with the former. An optimal configuration is achieved by placing the three round toneholes of 003–010 immediately above the bell tube, whose initial support the bone extension thus becomes.⁹⁰ In this way, the lower two holes of 003–010 align with those in 047, if it is also directly joined to the other bell tube (anyway, inverting it would put the long spacer 046 next to the bell, which is not impossible but seems less likely). Part 022 must then belong above 010, adding a single rectangular opening to a series of three round holes.

In this way we can finally get a grip on the original distances between upper and lower parts, direct evidence for which was destroyed together with the dolphin-hole tubes. The hole in 022 is physically connected to its own tailpiece, and virtually, through the alignment of two notes between 003 and 047, also to the other tailpiece. Being separated from the higher note of 047 by two positions, it appears likely that it played the same note as the slider hole above 047+046. In this way we can determine an optimal relative location for the two tails and in this way also establish the lost lengths. As a result, it seems that 209, if it really belongs here, should overlap with 227 by less than 5 mm, if at all. On the other hand, the fragment 200, broken at both ends, falls short of the required space by about 30–40 mm. The greater part of this apparent loss may be accounted for by first adding the short spacer 027 below 036 (fig. 7.54), where it becomes the exact counterpart of 150 below 050.

Thus we have accounted for all parts except spacer 130, which is finally required at the top of the pipe whose upper end has not yet been brought to length, that is, above 034. It will presently serve an important purpose there.

The four large bulbs come in a somewhat larger (135, 137) and a shorter variety (136, 138), differing by a substantial 5 mm. Three of them have *syrinx* holes drilled less than 2 cm from their upper ends, but on one of the longer it is found on the spigot instead (135). As mentioned, the other longer bulb (137) is associated with 063 on an in situ photograph. For the hole on the spigot of 135, no counterpart hole is found in a tube, as is the case with 016+139 on the slender instruments. As far as the topmost sections of the present hypothesis are concerned, 135 could therefore not go into either 017 or 102, which are intact, but only into 130, which is missing a chunk precisely where the *syrinx* hole would have been. When 034 and 130 are aligned according to deformation and corrosion patterns, the missing region faces upward, where the *syrinx* hole is expected. In this way, the two longer bulbs are associated with both a left and a right pipe and both with a high and a low pipe. Consequently, the same is also true for the shorter bulbs.⁹¹

Here, as well, not all the extant reed-cone “feet” would fit with each of the bulbs, in terms of either internal diameters or the remaining parts of upper bulb spigots that would go into those “feet.” The most likely configuration appears to pair cone 106 with bulb 135; 118, with 136; cone foot 112 together with cone 146, with 138; leaving 108, whose lower part is lost, to 136. Once more these assignments are of no musical consequence, the overall lengths of the parts being practically identical. Whether the reed cones had been detachable and therefore potentially helped bringing the pipes in tune remains unclear.

90. The bone appears too thick to fit into a part with two layers of metal, which seems to determine the orientation of the piece.

91. Olga Sutkowska observes that the twin lines decorating the shorter bulbs 136 and 138 are nicely matched by similar twin lines near the end of spacer tube 102; whether there were corresponding lines at the heavily corroded end of spacer 017 is difficult to see.

Given the substantial weight of the instruments, one may wonder whether a movable construction may have jeopardized stability, especially when separating the end of a cone from the termination of the bulb, slipping it upward on the spigot extending from the bulb during tuning. On the other hand, those spigots were especially long, about 3 cm, so that a sufficient overlap may have been guaranteed even with a few millimeters less. At any rate, the general construction entirely resembles the tunable compounds found on other instruments.

Let us recapitulate the results so far. We have assembled evidence for four pipes, two of which are right-handed, and two left-handed. Two sport at least one “chimney” among four sleeve-less fingerholes at the top, while two start with only three such fingerholes, a bit further down, and had no chimneys. All four carried a single dolphin slider, but the two higher ones have also higher slider holes. Two have a short bulb, two a long one. Two end in very long tubes terminating in bells, two in rows of no fewer than five toneholes and have apparently had straight ends. Two had clockwise, two counterclockwise slider brackets. Since the hand position on all appears to demand that the slider knobs are located (roughly) on the upper side of the tube, the former are assigned to its right side, the latter to its left.

The association of all those twos is not straightforward, because in two cases, two of the pairs have joints at the same position, partly with loss of material, so that the tops and ends become roughly exchangeable at those points. In addition, in at least three significant instances, the distance between adjacent pieces cannot be established physically. This typically concerns wooden sections with a single metal layer; the catastrophic destruction probably occurred at points where the pipes had been folded into three roughly equal lengths by brute force.

The top parts indicate the handedness by the displacement of the thumbholes relatively to the index holes, by the orientation of the former where they were made in teardrop shape, and by the chimney, little-finger and slider-knob positions where these can be established. How did handedness, height and bracket direction relate to each other? From all other aulos finds we would expect pairings of “lower” with “higher” pipes, of course belonging to opposite hands, and also that the higher one went in the right hand. But what does “lower” and “higher” mean in this case? Among the pipes with chimneys, while the pitches of middle-finger and little-finger holes may well have been similar, the right-handed specimen features larger distances to thumbhole and index hole, making it “higher” in at least this sense. Were these paired, so that there was one instrument with three chimneys and one with none? In this case, each instrument would have had two identical slider notes. However, the coinciding lower fingerholes of the chimney pipes do not seem to support such a notion. More importantly, it appears impossible to establish a configuration where the two fingerhole sets without chimney would meaningfully become part of a higher and a lower pipe.⁹² On balance, it appears inevitable to create two functionally comparable instruments, each consisting of a higher pipe with chimney(s) and a lower without. Surprisingly, these would however be “mirrored” instruments: on one of them, the lower pipe would go in the right hand—as one might perhaps expect from an aulos for left-handed players.

Whatever stance we take on pairing, the symmetry of the slider brackets is broken in some way. If one wanted to assemble the two lower and the two higher pipes into separate instruments, the two pipes of each would have their brackets facing the same side, which does not appear a very natural construction. If the instruments are compiled from different pipes, on the other hand, each is symmetrical in itself—but one has the brackets inward, the other outward, which is also awkward. Whether the engineers of these instruments would rather want to conceal or expose the slider movement, we would a priori expect them to be consistent in this respect.

Weirdly, it is precisely this inconsistency that may turn into one of the strongest arguments for the four pipes being conceived as an ensemble, not only for one musician to have, but for two musicians to play them side by side. After all, this is perhaps also the only way to explain “mirror” instruments

92. Since the long bulb 137 was found in 063, pairing the chimney-less tubes would entail placing the other long bulb, 135, above 028, including the spacer 130, which we found is the only one to entertain the *syrinx* hole of 135. As a result, already the twice three highest fingerholes become hopelessly misaligned (the lower two of 028 sit between the higher two of 063), while the distribution of slider compounds and end parts becomes intractable.

in the first place. When such a set was commissioned, the producers would have found it easy to drill holes at different positions as well as attach sleeve knobs or position slider knobs at opposite sides. The production of inverted slider brackets, on the other hand, might have demanded entirely new templates—and the craftsmen might either have dismissed this additional challenge, or used prefabricated pieces all designed for ordinary pairs, or indeed have forgotten about inverting this construction detail. As long as no more plausible explanation for the inevitable symmetry break is proposed, we may therefore draw two conclusions. First, the typical bracket orientation more probably pointed inward, as is the case when the low-left and the high-right tops are paired; therefore, exposing its movement to the public was apparently not desirable. Second, the two instruments can hardly have been designed for a single player. One person playing one of them at a time would hardly switch between a left-handed and a right-handed design. Were they commissioned for being played together in a symmetrical, and therefore almost certainly highly representative setting, such as Amanishakheto's funeral, or already before, as part of her state pomp? As enticing as the notion is, it is difficult to reconcile with the evidence, at least at a visual level. Hand positions a little further up or down a pipe may be regarded as sufficiently noticeable to be regulated in the choreography of imperial power, but they are hardly the most striking feature. For a symmetric design, we should above all expect symmetry between the two different types of ends—flaring bells and straight ends respectively being appointed to inward and outward orientation. This is not what we get. Most probably, both instruments sported a slightly shorter bell at the right and a slightly longer straight end at the left side. In this manner, the general appearance would probably restore precisely that typical arrangement of low and high as long and short that the internal design of the instruments defies. We find such a combination of longer straight left-hand and flaring shorter right-hand pipes on the small “Berlin aulos” from Egypt. Here the presence of the bell has been interpreted as visually balancing the length difference, and this may well have been one traditional design.⁹³ A less likely alternative can be gained by exchanging the top parts with three fingerholes, resulting in one pair with two flaring ends and one with straight exits. Visually, this configuration is perhaps the least plausible for a common performance. While two visually nonmirrored instruments being played side by side would blend in the generally nonmirrored appearance of people in a procession, it is difficult to see why one would have two different-looking instruments without any technical or musical necessity. It seems we have to accept the notion of a pair of superficially similar instruments with opposite and therefore symmetrical handedness on a more technical level. Unless issues of handedness formed an intrinsic part of Meroitic cultural expression, we should perhaps not dismiss the notion of one left-handed player too rashly.

In order to discuss the potential arrangement of the established lengths, it will be convenient to label these in a more readable way. The tops are easily classified into “higher” and “lower,” on the one hand, and “left” and “right,” on the other. The “higher” ones are associated with chimneys as well as slider brackets at the left side, while the “lower” ones have the brackets at the right side. We may abbreviate them as THL, THR, TLL, and TLR. The central parts are conveniently named after their slider tubes: C032, C036, C050, C085. The two ends with flaring bells are associated with two and three round holes, respectively: EB2, EB3, while the straight end parts with many toneholes may once more be named from parts in their core compounds: E001, E041. Thus we can now state the results of the foregoing discussion in a very succinct manner.

Of the top pieces, only the continuation of THR, with the fingered section 100+131+039, two chimneys and slider section 050, nowhere includes a potential switching point. According to the above arguments, it would be part of the only unequivocal pipe design: EB3+C050+THR.

THL includes a single chimney within fingered 089+034 and must apparently be joined to C032, which, if we can trust the above reconstruction of the associated dolphin hole, ends after a rectangular opening in 094. Below, either E001 or E041 fit.

TLR, ending in broken 063, as well as TLL, with its preserved lower rim on 028, might both go with either C036 or C085. The former of these central parts is tied to EB2, while the latter may alternatively accept either E001 or, just possibly, E041.

93. Hagel 2010: 74.

This leaves us with two switching points and consequently four possible designs. Among these, some predilections have already surfaced in the preceding discussion. We are now in the position to evaluate them more systematically from a musical viewpoint, looking for maximal harmonicity in the various plausible configurations. However, this task is encumbered by an unusually large number of open variables. Apart from the standard question of optimal effective reed lengths, we must deal with four places where the tubing appears destroyed beyond much hope of retrieving the precise original lengths of connecting parts: 209/227, 200, the upper edge of 049 and the lower of 063. Here some experimentation is required to establish the most musical measurements, which may differ for the four general solutions. Even more problematic is the lack of internal tubing across wide stretches, given that the extant internal diameters clearly vary throughout individual pipes. The wider diameter in the bass sections with many fingerholes thus appears to counterbalance their additional length, so that the exit notes from all four pipes seem to have been identical or close to identical. For our calculations, we can only estimate lost diameters from those of adjacent sections, linearly interpolating between these where feasible. But this can at best approximate the original design, so that the predicted intervals need to be taken with a grain of salt. At least, we are likely to err on the conservative side: while we will rarely hit on a nice interval by pure chance, apparent tuning deficiencies may well be an effect of our insufficient data.

The problem of missing internal diameters is compounded by difficulties measuring the existing ones accurately. Calipers give good distances but fail at tubes that are deformed and no longer cylindrical. Measuring using paper scrolls helps in such cases but is extremely sensitive to accretions. Both methods yield too large results where cracks have opened up or splinters are connected with glue. In short, it is next to impossible to obtain a set of precise values using consistent methods—and this does not even touch on the question of internal variation in longer pieces, which is inaccessible to direct measurement. It seems, however, that these problems can be mitigated by virtually “smoothing out” the tubes to a certain degree, modifying the measured diameters slightly toward those of the closest measured neighbors. When adopting such a weighted mean, harmonicity values increase significantly (across all four pipes, by 6 percent of reasonable concords), indicating that variance in measured bore diameters may indeed inflate the original differences. For the following “smoothed” results, the measured values from each piece are attributed twice as much weight than those from its immediate neighbors.

Since there is reason to believe that the two instruments were built to play together, we can start from an evaluation of their overall harmonicity, looking for a maximum of consonances between all four pipes in addition to those established within each single one, for each of the four plausible configurations. Apart from the mere number of consonances, the predicted reed lengths may serve as a secondary measurement of plausibility. Since we must expect effective reed lengths within such a set of pipes to match closely, larger predicted differences must make a possible solution less appealing.

Figure 7.55 compares the results for all four options. The last one clearly leads in terms of harmonicity and is rivaled only by the second one in matters of reed variance. The remaining two lag behind on both criteria. It is especially the consistency between the two criteria which suggests, with due caution, to dismiss the two less satisfying configurations. As these are distinguished from the more successful ones by the association of the straight bass sections, the results basically confirm that E001 should be kept with C085, and E041, with C032. Of the remaining solutions, one establishes two instruments with different end types, one with two flaring bells and one with two straight ends, while the other suggests two similar-looking pairs with a bell on the left and a slightly longer straight end on the right. The latter, we have argued above, may also be more plausible in a set made for joint performance, and it is also the one with the highest predicted harmonicity. In the following, I will therefore focus mostly on this configuration. At any rate, most or all musical inferences hold also for the other. The pipes of the preferred solution will henceforth be referred to as HL (higher left-hand), HR (higher right-hand), LL (lower left-hand pipe) and LR (lower right-hand).⁹⁴ Their total lengths (without reeds) would be estimated as: HL: 1176 mm; HR: 1135 mm; LL: 1156 mm; LR: 1143 mm.

94. These are now assigned the following accession numbers: 24.35878 (HR), 24.3579 (LL), 24.3580 (LR), 24.3581 (HL).

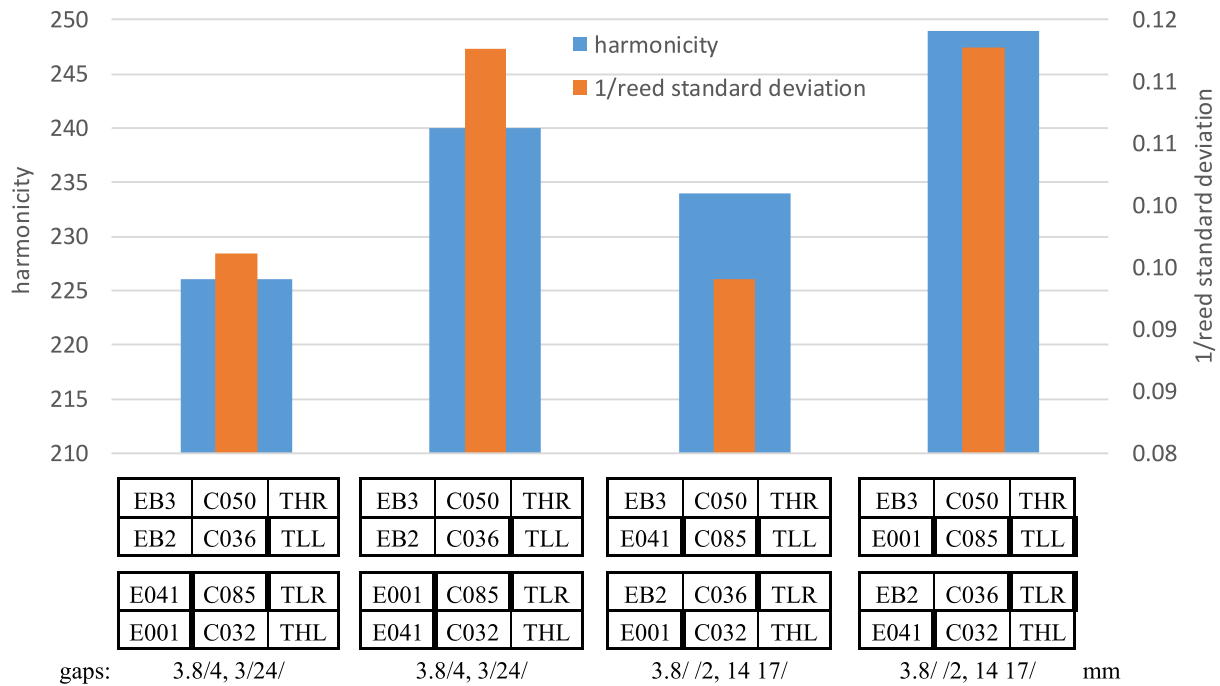


Figure 7.55: Possible configurations of the Long Pipes as two pairs. Reed internal diameters: 8.9 mm; holes below: open; internal diameters: smoothed; teardrop edges covered; harmonicity threshold: 20 cents. “Harmonicity”: observed maximum of pure intervals within and between pipes. “1/reed standard deviation: reciprocal of the standard deviation of effective reed lengths in mm.

EB3: 092+003–010+022	C050: 209+227+150+050	THR: 082–086+100+131+039+102+138+(112+146)
EB2: 049+047+046	C036: 200+027+036+121+077+076+006	TLL: 028+017+136+(118)
E001: 008+005+001–095–071–099	C085: 142+007+085+072	TLR: 063+137+(108)
E041: 033+026+087–096–098–009–041	C032: 206+094–097–029+061+032	THL: 089+034+130+135+(106)

Whatever configuration is accepted will finally have bearings on the likely attribution of dolphin parts 052 and 053 to slider tubes 036 and 085, respectively, based on a small but probably significant design detail. The upper edges of the slider rod extending from the dolphin tails up to the brackets are smooth on 050 as well as 052, but furnished with a series of tiny beads on 053 as well as, apparently, on 054, which is connected to 032, although the surface of the latter is blurred with corrosion. Assuming that similar designs belonged on the same instrument, the preferred configuration would thus assign 052 to 085, and 053 to 036. Although this conclusion may be of some concern for an actual reconstruction of the instruments, it does not affect their musical interpretation because the pitches predicted by the two options differ merely by 10 cents, and the respective overall harmonicity are all but identical.

7.2.2. Interpretation

7.2.2.1. Available Pitches

What were the musical capabilities of the two instruments, and how different were they, after all? Let us start from the general overview in figure 7.56, which reflects the results of the preceding evaluation for the most promising configuration.⁹⁵ It emerges that the instruments have enough in common to be addressed as organological variations on the same theme. First of all, all four pipes share the same bass note, a conclusion that appears reasonably safe since that very low note is little affected by the small

95. It will be noted that the predicted effective reed length of HL is significantly smaller than the others, and unrealistically so. This may be related to the lack of measurable internal diameters throughout the entire upper part of this pipe, right down to the dolphin hole, which probably featured a wooden core throughout. The tubing between the comparatively narrow bulb and the extraordinarily wide first bass hole section, whose profile would be crucial for assessing its precise acoustical length, is therefore unknown.

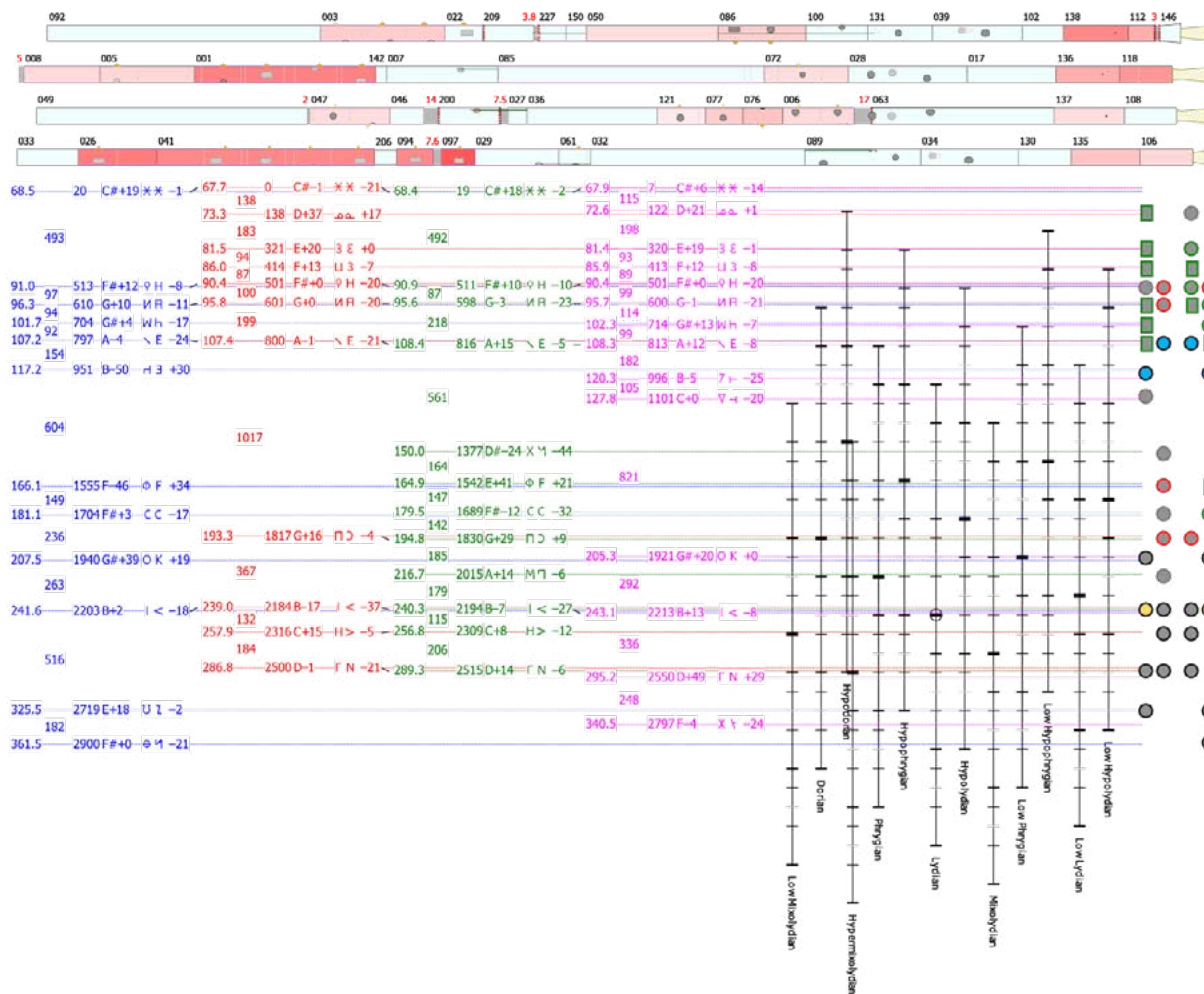


Figure 756: Inferred pitches and intervals of (top to bottom and left to right): L-HR (reed: 26.7 mm), L-LL (reed: 35.2 mm), L-LR (reed: 30.9 mm), L-HL (reed: 14.6 mm). Holes below: open, thumbholes closed, teardrop edges covered; bore smoothed; Lydian *hyperbolaia*: 487Hz (=490Hz – 10 cents). Harmonicity: 201/12/11/10/15 (threshold 20 cents). Top sketch: shades of red indicate internal diameters from 8.5 mm (light) to 9.8 mm (dark); extant slider lengths are indicated as green lines, extending downward over the slider holes. Right: schematic rendition of hole placements and shapes, in true handedness (opposite to the data columns to the left); blue: slider holes; yellow: chimneys with cross-fingering capability; green: triangular knobs; red: ring-shaped knobs; gray periphery: knob shape unknown; black: holes without sleeves.

possible variations of uncertain lengths. From there, an almost uninterrupted sequence of semitones just stops short of the slider notes. The lower part of the sequence materializes only on two pipes, which both omit the third lowest semitone. On the other two, the toneholes start only a fourth above the bass note. The slider notes generally stand on top of a larger interval; they are one step higher on the higher pipes. HL is unique in including another semitone above the slider note; using it would make the slider useless, as would using any other note between little finger and slider. Such notes are otherwise only found on the right-hand pipes and above their slider tubes. HR has two of them; HL replicates these, but adds one or two more, depending on whether one finger is occupied solely with working the slider or also operates a fingerhole. The two low pipes are in a sense complementary, since their full potentials emerge in different regions: while LL has many bass holes, LR abounds in higher notes. Nonetheless they remain fully compatible, each providing a subset from the other in its less favored region. Similarly, the two lower fingerholes on HL replicate those on HR.

The biggest difference between the two instruments concerns the highest notes overall. While the index and thumbholes on the lower pipes coincide, this is not true for the higher pipes. On the pair LR-HL we observe a quite traditional-looking offset of a single step: the thumbhole of the higher pipe (without opening the edge of the teardrop) corresponds to the index hole of the lower. The

interval to the treble note measures more than a regular tone. The pair LL–HR is physically much more demanding. Here the thumbhole already plays a tone above the index of the lower pipe, and the index basically adds another tone. This contrast between a taxing and an even more taxing instrument design is reminiscent of the two Late Classical auloi found in Megara. Though these are largely similar, the top index hole of one of them is drilled at a more convenient position but consequently falls short of the harmonic capabilities that the other instrument offers.⁹⁶ Similar differences have since also been observed in the Oxus find.⁹⁷ Conceivably the analogous difference between the instruments from Meroë was prompted by genuinely artistic motivations. On the other hand, since the two auloi are so similar in other respects, it is tempting to interpret it as reflecting the different physiques of two players to whose demands they were tailored.

Although some of the predicted pitches have turned out a bit fuzzy across the pipes—we always need to keep in mind that due to missing data they are often approximations—it is straightforward to associate them with ancient notes: the inferred tuning deviates from $f' \leq 490$ Hz by no more than about the twentieth part of a tone. The lowest note from any toneholes is thus defined as ancient $\underline{\alpha\alpha}$ (B'), which is at the same time the lowest note in the system of *tónoi*, being the Hypodorian *proslambanómenos*.⁹⁸ The common pipe exits therefore sounded a pitch outside any regular ancient key. However, the transmitted note signs went a few steps even below Hypodorian; the pitch in question was notated as $\times\times$ (C').⁹⁹ Fascinatingly, this lowest note of all aulos finds is at the same time the lowest attested note in the extant ancient melodies: when announcing a prophecy in the middle of an aria partially preserved on papyrus, the voice drops to the lower octave down to this very pitch.¹⁰⁰ But this may be coincidental; probably the extra semitone comes as a corollary to the idea of sounding all notes in the system consistently from sideholes.

Instead of the late–antique fifteen–scale system, Aristoxenus’s older thirteen keys are printed in figure 7.56. While coming with different names mostly for the sharp keys at the right side, these are otherwise structurally identical, apart from missing the highest two *tónoi*, Hyperlydian and Hyperaeolian, which anyway are of no interest for the present low–pitched instrument. From the inherent semitone grid, we can easily read the probable identity of all the bass notes. Above the Hypodorian *proslambanómenos*, the missing semitone would be associated with “Low Hypophrygian” (later: “Hypoiastian”), which is none of the traditional keys and even fails to gain track in the extant melodies from the Roman period.¹⁰¹ The next present note, \mathfrak{ZE} (D'), is the Hypophrygian *proslambanómenos*, while it also continues the Hypodorian scale, as does the following semitone, $\beta\omega$ ($E\flat$, showing up as \mathfrak{LZ} in the chart, in the way the same pitch is notated in Hypoiastian and Hypoaeolian). Both Hypodorian and Hypophrygian are mentioned in connection with Greek tragedy and described as modes used exclusively by the actors, not the chorus.¹⁰² The Hypolydian *proslambanómenos*, $\varphi\eta$ (E), is the first available on all four pipes, followed by the Dorian, \mathfrak{IF} (F). The next semitone, \mathfrak{WH} ($F\sharp$), being the *proslambanómenos* of nontraditional “Low Phrygian” (later: “Iastian”), is once more omitted on two, but present on the others, probably for its occurrence in the Hypolydian. Of special importance is the following Phrygian *proslambanómenos*, $\backslash\mathfrak{E}$ (G), which we not only find on all pipes, but on two of them as the slider note and therefore one that was considered essential to have available even when alternating with another, lower bass note. The semitone above is left out as harmonically inconspicuous; besides forming the *proslambanómenos* of another nontraditional key,

96. Terzēs and Hagel 2022: 60.

97. Hagel 2025: 109–10.

98. See, e.g., Gaudentius 22, p. 350.23–352.2 Jan.

99. Aristides Quintilianus 1.11, p. 24–27 Winnington-Ingram.

100. Pap. Yale CtYBR 4510, Pöhlmann and West 2001 no 41. For the identification of the pitch, see Hagel 2009a: 300–302; note the uninformed author’s naïve assumption that “no lyre or aulos can have had such an ambitus.”

101. Only one larger fragment, Pap. Oxy. 4467 (Pöhlmann and West 2001 no 58), and a single line on papyrus, Pap. Berlin 6870.23 (Pöhlmann and West 2001 no 18) lend themselves to a purely Hypoiastian interpretation (see Hagel 2009a: 279–80), while another, Pap. Oslo 1413a.1–15 (Pöhlmann and West 2001 no 39), ventures into that key in the course of modulation (see Hagel 2000: 293–99). Hypoiastian is, however, acknowledged as an auletic key in one of Bellermand’s Anonymi, §28.

102. E.g., [Aristot.] *Problems* 19.48.

Aristoxenus’s “Low Lydian” (later: “Aeolian”), it only functions as *parypátē* in Hypodorian and Dorian and as the chromatic variant note in Hypolydian.¹⁰³

The slider holes of the higher pipes are realized on the next step, which should bring us to ζH (A), the *proslambanómenos* of the Lydian, the central key of ancient notation. Surprisingly, though, the respective hole on HR appears a quartertone too flat. The “required” pitch is realized on HL, although even here it appears somewhat flatter than expected, standing only a “small tone” above its lower neighbor, instead of a full tone. Only on HL do we encounter another hole in the bass region, situated between slider hole and slider tube. Placed a semitone above ζH (A), it must represent ∇H (B \flat), the *proslambanómenos* of “Low Mixolydian” (later: “Hyperdorian”). Mixolydian was long recognized as the highest *tónos* of a canonical seven, even though its precise location relative to the others was disputed. Before Aristoxenus, two harmonic schools had come up with different solutions, a semitone apart. Aristoxenus incorporated both options as “Lower” and “Higher Mixolydian” (and duplicated other keys accordingly, in order to obtain names all around the circle of fifths).¹⁰⁴

The preceding observations appear to hold the key to the general design of the bass region: overall, the toneholes below the slider tubes range precisely from the lowest to the highest *proslambanómeno*i of the seven classical *tónoi* (or, as we should perhaps call them in this context: *trópoi*). The ensemble thus proclaims the totality of music, at least in a specific, probably specifically Hellenistic, context. Even in a significantly later text from Bellermann’s Anonymi, the same seven keys whose lowest notes we have found defining the low toneholes of our instruments are mentioned as those used by “orchestic” musicians, to the exclusion of the other five or eight.¹⁰⁵

The apparent placement of the Mixolydian a semitone above Lydian instead of a tone allows us further to pin down the musical heritage of the instruments: in some distant way, they stand in the harmonic tradition of the particular system which Aristoxenus asserts was brought about by the need of creating (modulating) auloi, and which I have therefore dubbed the “auletic system.” In contrast to its rival, whose reliance on tones and semitones and thus the circle of fifths warrants the designation “commensurable,” the distances between the constituent scales of the “auletic system” included odd intervals of three quartertones. In the more than three centuries between the invention of that system and the conception of the Meroë auloi, the art of the aulos had of course undergone deep-reaching transformations, not least by the transition from bone instruments with occasional metal parts to fully metal-clad tubes with rotary sleeves. Perhaps most importantly, Hypodorian ceded its old place one tone below Dorian to Hypolydian and was relocated to a fourth below Dorian, so that three “Hypo-” keys now followed the same rationale. This crucial redesign, which has proven so influential for Western music theory, is already found in Aristoxenus’s disposition. Evidently, it is also adopted on the Meroë auloi, whose lowest toneholes play Aristoxenus’s Hypodorian, while the earlier systems did not incorporate such a low key at all. Nonetheless the old “auletic” system may still have left its imprints on the instrument design—musical technology, where it defines performance practice, is often conservative, especially when established repertoire is handed down.

This might explain the peculiar flat Lydian slider hole on HR. Its predicted pitch, 154 cents above the Phrygian *proslambanómenos* on the same pipe, amounts to precisely the three quartertones that separated these scales in the “auletic system” as reported by Aristoxenus. Did the makers provide both for a more modern interpretation of Lydian on HL and for the ancient relations on HR, perhaps for different kinds of music? And is the evidence strong enough to warrant such a claim? Since the tube that connects the slider hole to the lower part is fragmented, our establishment of the interval in question on HR is based on optimizing overall harmonicity, on the one hand, and on making the lower notes coincide across pipes,

103. For the harmonic inferiority of *parypátē*, see, e.g., Hagel 2022: 162–74. The same pitch might also serve as enharmonic *likhanós* in the narrow variant of this genus that Aristoxenus preferred.

104. For the reconstruction of the early systems, see Hagel 2000: 165–82; 2009a: 378–93.

105. Anon. Bell. §28, using late antique fifteen-scale terminology and enumerating the keys from high to low: οἱ τοῖς ὀρχηστικοῖς προσήκοντες μουσικοὶ ἑπτὰ τούτοις χρωματῶνται: ὑπερδωρίῳ, λυδίῳ, φρυγίῳ, δωρίῳ, ὑπολυδίῳ, ὑποφρυγίῳ, ὑποδωρίῳ. “The musicians concerned with dance performance use the following seven: Hyperdorian, Lydian, Phrygian, Dorian, Hypolydian, Hypophrygian, Hypodorian.”

on the other. Indeed, when the distance is tentatively increased to about the interval we find on HL, the pitches immediately below become misaligned and overall harmonicity drops. Also, while increasing the distance below the hole may lead to a more regular interval between Phrygian and Lydian within HR, this should rather not be done by lowering the Phrygian but by raising the Lydian. But there is hardly any leeway for such an adjustment because the slider-hole position is well defined, the slider still being corroded in place on 050, and internal diameters can be measured on both 050 and 086. On balance, we have good reason to believe that the interval was indeed smaller on HR than on HL, even though this is difficult to prove beyond doubt. For perspective, it must be noted that the present author would be more than happy with corresponding pitches and has certainly no motive unnecessarily to complicate the picture further with the introduction of an older tonal paradigm along a more modern one.

The upper part of the instruments contrasts strongly with the comparatively neat semitone grid in the bass region. Here we find several intervals predicted that are close to odd multiples of quartertones like the peculiar distance between Phrygian and Lydian on HR, or at any rate closer than to any “regular” interval. This is not surprising, given the challenging hand spans, which impose close limits on the distribution of fingerholes between the extremes. In certain cases, the required pitches must then have been accessed by skillful manipulation, potentially including variation of lip pressure along half-covering of fingerholes—evidently an old technique in the art of the aulos—and, in special cases, cross-fingering. Once more, similar requirements are posed by the instruments from Megara and the Oxis temple. In such circumstances, determining the intended scales becomes an intricate endeavor, fraught with uncertainties.

All the more important is it to get what we can get right as right as we can. For two reasons, we need to pay more attention to the question of open or closed holes below the one played at any given time here than in other known auloi. First, in spite of the numerous toneholes, the hand positions are fixed to the highest of each pipe, so that much fewer combinations of opened and closed sleeves make sense than on instruments where the hands may play in different regions, such as the shorter pipes discussed above. Second, while thanks to the thin tube walls and the large size of the toneholes in relation to the bore, cross-fingering would generally not affect the pitch of an aulos hole sufficiently to play two functionally different notes from it—as opposed to different tuning shades—the case is different when “chimneys” are involved. Since these effectively increase the wall thickness to a value that is comparable to the distances between toneholes, the hole below them becomes much more involved in defining the pitch.

Above all, we must pay attention to the little-finger holes. Although two pipes (in the most plausible configuration, the two right-hand pipes) feature toneholes right below these, it is unlikely that those toneholes between hand and slider hole were typically used. After all, leaving them open during a performance renders the entire bass section useless, including the sliders, thwarting the very point of the long instruments. The sheer existence of the holes in question is of course sufficient evidence that they were used sometimes, and it may be crucial that, on the preferred hypothesis, each pair contains only one pipe with such holes, so that bass notes would have been available in any disposition. At any rate, a prudent evaluation of the most typical pitches must start from the instruments in their fullest potential, including operational sliders and the ensuing additional available pitch, and therefore closed toneholes below the little fingers. This will most remarkably affect HR, where the little finger also plays on a chimney.

In addition, the exorbitant hand span makes it difficult to release thumb and middle finger at the same time. In order to ensure a steady grip, it appears preferable to keep the latter firmly on its hole when the former uncovers its hole, rolling upward. At least on the lower pipes, the ensuing effect on the pitch of the thumbholes is not negligible, because there the two holes are only separated by a small interval.

Figure 7.57 appears to vindicate these considerations, showing that by including the effects of plausible “cross-fingering,” overall harmonicity still grows considerably (i.e., by 6.9%). Notably, almost half of this improvement is caused by the resting middle fingers. Are the differences merely statistical noise? If they are genuine, it would be fascinating to find such a detail of ancient instrumental practice imprinted on pipe design and indeed detectable by the means of modern technology.

Given the caveats about hand physiology, a surprisingly high number of predicted pitches appear harmonically meaningful without further manipulation. Above all, the single note that the upper halves of all four pipes share is Lydian *mésē* |< (*a*), the ancient system’s pivotal note. However, the disjunctive

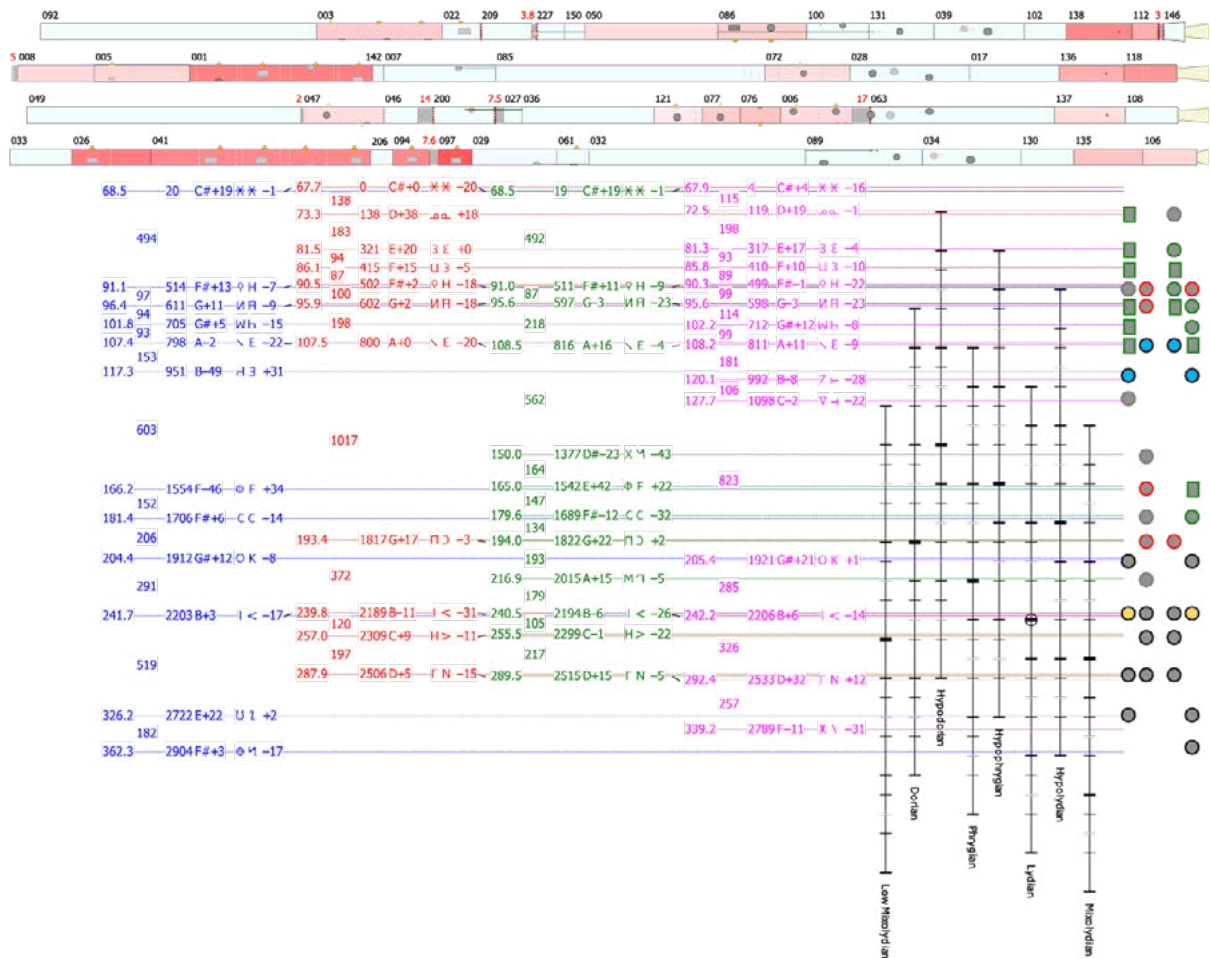


Figure 757: As fig. 756, but with adjacent lower holes closed when playing the notes from little-finger and thumbholes. L-HR (reed: 23.9 mm), L-LL(reed: 31.9 mm), L-LR (reed: 30.7 mm), L-HL (reed: 12.1 mm). Harmonicity: 220/11/11/9/15 (threshold 20 cents).

whole tone above it is missing, being replaced by the semitone of the conjunct tetrachord that is part of Phrygian and Hypophrygian (*b* \bar{b} , notated ΘV as diatonic and chromatic *trítē*, but $H >$ as enharmonic *paranētē* and also as Mixolydian *mésē*). This preponderance of the Phrygian reflects the presence of four Phrygian as opposed to merely two Lydian *proslambanómenoí* among the bass notes. In contrast, Phrygian *mésē* is only found on LR. Both lower pipes provide Dorian *mésē* $\Pi \Delta$ (*f*), however, which is also required for Lydian and diatonic Phrygian. The respective note on HR is a quartertone higher and may thus be useful for the highest note of a Lydian enharmonic *pyknón*.¹⁰⁶ Below, already beyond the fingered notes, the two respective pipes provide the Hypolydian *mésē* and Lydian *hypátē* CC (*e*), which may also have been of importance in its role as Hypophrygian *paramésē*. If the corresponding hole is opened on HR, the pitch from its upper neighbor, which is equipped with the smallest chimney, rises by more than a quartertone, to sound Hypolydian OK (*f* \sharp) (see fig. 7.56). In this way, turning a single sleeve apparently switches between a more Hypophrygian-Lydian and an expressly Lydian-Hypolydian mode.

The three lowest notes in the upper region appear to stand at three-quartertone intervals, which brings us back to the question of compromising between the harmonic standard of theory, which modulated along the circle of fifth, and the old three-quartertone offsets that reflected the players' physiology better. It may be significant that the distance of a small whole tone between Phrygian and Lydian *proslambanómenos* that we found on HL is precisely reflected between the *mésai* of the same keys on its counterpart pipe LR, an octave higher. On the other pair, the Lydian bass note on HR can only be played when the Lydian *hypátē* is permanently closed, so that the interval between these never matters. Still, it seems to

106. For traditional three-quartertone *pykná* as opposed to Aristoxenus's narrower standards, see Hagel 2009a: 397–429.

be at odds with the Lydian *mésē* on the same pipe, whose straightforward pitch was certainly not lower than those from the corresponding holes on the other three pipes. However, being played on a chimney hole, its pitch is once more affected by cross-fingering. When the adjacent little-finger hole is covered, its predicted pitch drops by about a quartertone (to 236 Hz), to about an octave above the bass note (calculated as 1212 cents). Once more it seems plausible that the chimneys not only served to make pitches accessible that would otherwise have been out of reach, but were also taken advantage of in terms of their capabilities for cross-fingering. Quite possibly, finger spans provided enough leeway to determine the precise location and height of the chimneys with a view to the notes they would produce with and without cross-fingering.

This appears to be confirmed by the third chimney, the upper one on HL, whose height is again unique. When the little-finger hole is covered, its pitch drops by a somewhat larger amount (67 cents, to 233 Hz), resulting in a note that has no bass counterpart but may serve as the otherwise missing Dorian and Hypodorian *trítē* $\Lambda\zeta$ (*ab*).

The top note of the lower pipes is $\Gamma\mathbf{N}$ (*c*, notated $\mathbf{E}\mathbf{U}$ in diatonic/chromatic and $\Delta\mathbf{\square}$ in standard enharmonic Lydian). This is the top note of the old system, a fourth above Phrygian and a fifth above Dorian *mésē*, and was predicted to form an important aulos top note long before archaeological evidence emerged, on the basis of textual evidence and melodic statistics.¹⁰⁷ That it was typically the top note of the lower pipe, however, was not clear, although at least one such aulos design had also been reconstructed, both theoretically and experimentally.¹⁰⁸ The higher component of that hypothetical instrument was supposed to reach two steps further upward, in fact up to the top note of the kithara, *nētē* $\Theta\mathbf{M}$ (*e'*).

Since then, the Megara auloi have confirmed the predictions both regarding a top note $\Gamma\mathbf{N}$ (*c*) and a higher pipe exceeding it by two steps, albeit of variable size. More recently, the Oxus fragments, being remains of various instruments, yielded evidence both for left-hand pipes with the same top note and right-hand pipes that reach either one or two steps higher.¹⁰⁹ Its precise pitch may vary: while the early instruments from Megara are overall tuned almost a quartertone higher, those from the Oxus temple ($\Gamma\mathbf{N}$ at 285–287 Hz) are close to the long auloi from Meroë (288–292 Hz).

On these, the highest fingerholes appear well-integrated in the harmonic framework, as opposed to merely offering as much additional range as possible for a given player, while leaving the intonation to their individual skills. On HL, where only the index hole rises above the range of the low pipes, it plays an eleventh above the highest bass note and a fourth above the thumbhole of the lower pipes. One would need to partially cover it in order to access $\mathbf{U}\mathbf{L}$ (*d*), which is most important in Phrygian, but also part of (diatonic) Lydian and chromatic Dorian. That note is directly provided on HR. Given that pipe's offset of two fingerholes, we find it assigned to the thumb. It stands a fourth above the ubiquitous Lydian *mésē*, $\mathbf{I}\zeta$ (*a*). The index hole, finally, sounded a fifth above the same note, providing Lydian *nētē* $\Theta\mathbf{M}$ (*e'*).

What would fully opening the edges of the teardrop-shaped thumbholes entail? On the higher HR, the predicted pitch (about 340 Hz) stands a semitone (108 cents) below the index note.¹¹⁰ It has no place in Lydian, but is found in Phrygian (*eb'*), both diatonic/chromatic ($\mathbf{h}\mathbf{7}$) and enharmonic ($\mathbf{X}\mathbf{v}$), and in diatonic Dorian ($\mathbf{X}\mathbf{v}$). The Phrygian chromatic *pyknón* is completed by the index hole, whose note would then, confusingly enough, also be written $\mathbf{X}\mathbf{v}$ (*e'*). Phrygian enharmonic, in contrast, might be played by opening the teardrop edge in two steps.

The thumbhole on HL is only partially preserved, but there is no doubt about its teardrop shape, analogously to the thumbhole on HL. The missing lower end however encumbers the prediction of its pitch. Assuming that the difference was not significantly smaller than on the other teardrop hole, we obtain a note that may be read as Lydian chromatic $\Delta\mathbf{\square}$ (*c#*) or Dorian $\mathbf{B}\mathbf{7}$ (*db*) (none of the keys in

107. Hagel 2009b, 2009a: 34–38, 343–51.

108. Hagel 2009a: 397–412.

109. Hagel 2025.

110. As discussed above, the pitch of a partially covered hole cannot be predicted with any accuracy. On the probably more realistic assumption that, in partially closed state, the thumb covered a millimeter more than just the edge of the teardrop, the difference between this and the fully open hole on HR measures about 98 cents. Overall harmonicity remains virtually unaffected.

between includes a note at this position). More importantly, perhaps, this note stands an octave above the last hole above the slider tube on its companion pipe.

In both cases, the harmonic interpretation of the teardrop-shaped holes thus entails that opening them fully would produce harmonically secondary pitches. An analysis of corresponding harmonicities confirms this: with fully open holes, the optimized values drop noticeably.¹¹¹

For all the readily available pitches from all of the seven ancient keys, whether accessible directly, by cross-fingering or with the help of tear-drop-shaped elongations, we finally need to address a blatant hiatus in the musical map of the instruments: Lydian *paramésē* ΖϚ (b) is missing. Though it would not be particularly difficult to produce its pitch by half-covering any of the fingerholes for ΓΝ (c), the absence of any positive material indication that this was done, such as an elongated shape of any of these, still leaves room for puzzlement. But this apparent deficit may actually form one of the most archaic features of the instruments. In the early systems, characterized by aligning the top notes of the individual scales at ΓΝ (c), the Lydian *tónos* was represented by a structure that Aristides Quintilianus transmits under the designation of “Taut Lydian” (*sýntonon lýdion* or *syntonolydistí*) taken from Plato’s *Republic*.¹¹² However, of all the *harmoníai* that Aristides details, Taut Lydian is the most limited, spanning merely a minor sixth with no more than five notes. Consequently, it forms a gapped scale—and the most conspicuously omitted regular scale degree is none else than its *paramésē*. It thus emerges that the Lydian of the Long Pipes is by no means deficient in terms of the ancient *harmoníai*—which in turn may have been informed by the organological predecessors of our instruments.

7.2.2.2. Tonehole Shapes

When talking about toneholes and their pitches, we have so far avoided discussing one of the most enigmatic features of the instruments: the alternation of round and rectangular holes in the bass region, including one rectangular hole above the slider tube of HL (see figs. 7.56 and 7.57 above). What was the purpose of those much larger openings? On the one hand, larger holes are likely to produce louder notes and may thus be associated with pitches of harmonic priority. On the other, large openings may remain sufficiently large for good tone production even when they are somewhat reduced: for this reason, the rectangular holes may be especially well-suited for tuning their pitches with greater precision in the context of an individual performance. This appears to be true for at least one such hole from the Oxus find; a slider of unusual design on one of the Megara instruments has also be explained along such lines.¹¹³ Again, tunability may mean very different things. Possibly, it ensured a perfect pitch for the harmonically most important notes. Yet in the context of ancient harmonics, the opposite might be true just as well: smaller round holes might represent the harmonic framework of “fixed” notes, while adjusting the sleeves to cover the large rectangular holes to different degrees might reflect the concept of “moving” notes within the tetrachord. However, when progressing through the various keys for which the instruments provided, what is a “moving” note in one becomes a “fixed” note in another, preventing binary ascriptions. Anyway, no simple dichotomies will unlock the secret, because the pipes display divergent propensities toward hole shape, so that in several cases the same note is sounded by differently shaped holes on different pipes. All we can hope for is to detect potentially meaningful tendencies.

Looking for such tendencies demands quantifying the two criteria in question: the inclination of a particular pitch toward round or rectangular holes in terms of percentages of each option, on the one hand, and the categories of harmonic function in the various pitches within the seven old *tónoi*, on the other. The second criterion can be expressed in more than one flavor, depending, above all, on whether the chromatic genus is considered along the diatonic or not. A survey of the different options within the bass region up to the slider holes reveals various degrees of correlation, the strongest of which associates

111. 206/9/10/11/11: a drop of 6.8%.

112. Aristides Quintilianus 1.9, pp. 18–19 Winnington-Ingram. It is possible to identify this “Taut Lydian” as the precursor of the Lydian *tónos* because it is this scale that, when it is aligned with the others at the top ends, will project its *mésē* to the respective position relative to the others.

113. For the Oxus auloi, see Hagel 2025: 85–87, 120, 122; for the Megara slider, Terzēs and Hagel 2022: 56–57.

the diatonic “moving” notes with rectangular hole shape.¹¹⁴ This is certainly not the whole story, because it does not provide a motivation for every hole shape. Nonetheless it indicates that loudness was not the primary purpose of the larger type of hole and probably not a purpose at all, while the opportunity of fine-tuning individual notes may have played a crucial role in this respect. Analogously, the single rectangular hole above the slider tubes, which we find on HR, may have been intended to adjust its pitch to a more regular variant of Φ (D), a fourth below Phrygian *mésē* \mathbb{M} (g). On LR, where the same position is occupied by a round hole, a less pronounced but perhaps noticeable lowering effect may have been achieved by closing the additional hole below.

7.2.2.3. Knobs

Just as the shapes of the toneholes, those of the knobs for operating the rotary sleeves appear to defy a rigid musical categorization, while still exhibiting certain tendencies. The knobs come in two types, a more common triangular and a less frequent ring shape (they are distinguished in figs. 7.56 and 7.57). Since the former sit on large, almost rectangular bases, while the latter cling to the tubes on somewhat spidery “feet,” it is generally not difficult to establish the general shape of a knob wherever substantial traces of its soldering position are discernable. Apart from the sections to which extant ring-shaped knobs could be assigned with near certainty (003, twice 047, 072, 077), it thus appears that one of those in part 006 also featured such a knob.

It emerges that all ring-shaped knobs are associated with round toneholes, although there are also round holes with triangular knobs. In the bass region, rings are particularly found above the two long end sections terminating in bells, while the compounds with many bass holes may have had triangular knobs throughout. In the proposed reconstruction, only pipe HL may have sported no ring knob at all, while it is not unlikely that its companion LR was only equipped with this type (the traces on 121 seem too short for a triangular knob, but the two remaining positions are unfortunately destroyed). On the other pair, each pipe would have had at least one ring-shaped knob. With such knobs on 072 as well as 006 and 077, it appears impossible to rearrange the large parts in a more consistent way, collecting all ring knobs on merely two pipes (and preferably those ending in bells). Apparently we must live with some tantalizing variability on these instruments.

Regarding the notes concerned, two of the four extant ring knobs on LR find counterparts on another pipe. The higher of these pairs is associated with Dorian *mésē* Π (f), the lower with Hypolydian *proslambanómenos* Ψ (E). The remaining two ring-knob notes, on LR, operate Hypophrygian *mésē* Φ (D) and Dorian *proslambanómenos* \mathbb{M} (F), but since the surrounding knobs are lost, we cannot know whether these notes were actually singled out. All determinable positions, at any rate, form part of Hypophrygian.

7.2.2.4. Music

What kind of music may such pipes have played? As we have seen, being designed for the seven ancient keys, they appear associated with “orchestic” musicians by Bellermann’s Anonymus, in contrast to the music of organ players, citharodes, and aulos players. The latter are said to use *tónoi* ranging from Phrygian to Hyperaolian—from two flats to four sharps, if Lydian is transcribed as the natural key. The seven keys, in turn, range from five flats to a single sharp. Those of the “aulos players” conform with the musical documents from the Roman Imperial period, dating from the second to fourth centuries CE, while the “orchestic” keys are found in those from the Hellenistic era, specifically the third and second centuries BCE. Whatever kind of music the Anonymus’s “orchestic” refers to, it is difficult to imagine dance performances accompanied by an instrument playing in various *tónoi* that is not some kind of aulos. A priori, we would therefore assume that the text’s *aulētai* are solo performers, while orchestric activities were not perceived as defined by their accompanying instrument. Indeed, such accompanists are

114. The corresponding correlation coefficient is 43%; compare 19% for moving notes including *khōmatikai*; 40% for *parypátai* only; 11% for non-*proslambanómenoi* (of 21%, in an exclusively diatonic framework). A binary distinction between possible *parypátai* and pitches that are never found in this function would yield an even stronger correlation (50%); since diatonic/chromatic *parypátai* are enharmonic *oxýpyknoi*, one might be tempted to read this result as an indication that the rectangular holes were primarily meant to lower the note by a full quartertone, down to the respective *mesópyknon*. Such a conclusion would however be mistaken because a binary interpretation of such a kind leaves the three cases of rectangular non-*oxýpyknoi* unexplained.

often referred to as *khoraúlai* and thus set apart from *pythaúlai*. They competed separately at the musical contests, even though, as we learn from inscriptions, one and the same person might excel in both arts.¹¹⁵ Phrynichus Arabius, in the attempt to cleanse Greek language of non-Attic terms, demands that *pythaúlai* should be called “mere *aulētai*,” while offering the designation of *kýklios aulētēs*, “ring-(dance) piper,” for “the other one.”¹¹⁶ Apart from contests, *khoraúlai* are associated with stage activities,¹¹⁷ but not necessarily tragic performances.¹¹⁸ From this general picture, we might expect that our long auloi were related to those typically used to accompany choruses, whether dancing or at the same time singing and dancing. However, Aristides Quintilianus, about two centuries after their burial, insists that choral auloi are in fact “suited for high pitch” (2.16, p. 85.7–8), a notion that is difficult to reconcile with the obvious importance of their bass region, even though, admittedly, the hands always played in the top position.¹¹⁹

Be that as it may, we have extensive fragments of two compositions from the Hellenistic period, not much more than a century before Amanishakheto’s death, that were performed by a chorus and accompanied by at least one aulos as well as kitharas.¹²⁰ As showpieces of an Athenian cult embassy to Delphi, they were inscribed on the walls of the Athenian treasury there and, after their rediscovery in the late nineteenth century, became famous as the “Delphic Paeans,” the most elaborate surviving examples of ancient music. Their topics and style are similar, but one was written with the signs of the “instrumental” notation by the cithara player Limenius, while the composer of the other one, a certain Athenaeus, used “vocal” notation, consisting of ordinary letters. The relation of Limenius’s piece, which is centered on the natural signs, to the larger system of notational keys may be disputed—was the string player accustomed to writing in transposing notation?¹²¹ At any rate, Athenaeus’s score is clearly Phrygian, with modulations toward Hypodorian.

Given its large ambitus of an octave and three tones and its exuberant chromaticism that has puzzled scholars and modern audiences alike, it is highly instructive to compare the tonal material of Athenaeus’s Paeon with the tonal capabilities of our potentially choraulic instruments. In figure 7.58, the notes of the Paeon are indicated by colored circles. Apart from diatonic Phrygian with chromatic modulation into Hypodorian as well as the treble notes, we find stray pitches that belong in the Dorian (B *db*) and, at least according to regular analysis, Mixolydian (O *f#*), although the latter is used in surprising ways, forming an alternative chromatic fourth together with Y (*eb*), M (*g*), and Λ (*ab*).

The coincidences between the song and the instruments are certainly stunning. The lowest note of the voice (which occurs only in the archaizing first section) is the highest in the combined bass regions, followed by a gap of a major third, up to the lowest note of the higher region that is available on both instruments. Only the following semitone where the instruments provide a three-quarter-tone interval is problematic (marked in red in the figure). Closing the sleeve of the hole below does not help either, because it merely reduces the interval by the twentieth part of a tone. In order to get within the range of a semitone, one would need to down-tune the respective tonehole itself by diminishing its transversal diameter by about 3 mm with the help of the rotary sleeve. This would likely compromise tone quality—but then, a weaker sound for the harmonically weaker *parypátē* might have been acceptable.¹²² The modulating surprise note O (*f#*) is available on both higher pipes. If its introduction appears slightly

115. E.g., Fouilles de Delphes 3, 6.143. For further references, see West 1992: 93 n. 63; Moore 2012: 60–61.

116. *Elogae* 138: Πυθαύλης μὴ λέγε, ἀλλὰ φιλὸς αὐλητῆς, ἐπεὶ καὶ ἄτερος κύκλιος αὐλητῆς. See CIG2758 (Aphrodisias), changing from one designation (1.11; 3.1.5) to the other (4.2.2; 5.2.2). Less specifically, Ptolemy XII “the Aulete” reportedly acted as *khoraúlēs* (Strabo 17.1.11).

117. *Apostolic Constitutions*. 8.32. In his catalogues of activities unsuitable for Christians, Ephrem the Syrian regularly lists *khoraullia* next to dancing (*orkhēsmoi*, *orkhēsthai*, *ballizein*).

118. *Anthologia Graeca* 11.11.

119. In principle, the presence of *sýrinx* holes on all four Long Pipes (but, as far as we see, only a single one of the others) might also count as making them “suitable for high pitch” (ἐς ὄξύτητα εὐχερές, as opposed to generally high-pitched), and thus give Aristides’s wording a very precise motivation; not knowing how often those overblowing devices were actually employed, it is impossible to assess the plausibility of such an interpretation.

120. See Bélis 1992; West 1992: 288–300; Pöhlmann and West 2001 nos. 20–21.

121. Hagel 2009a: 40, 445.

122. See n. 103 above.

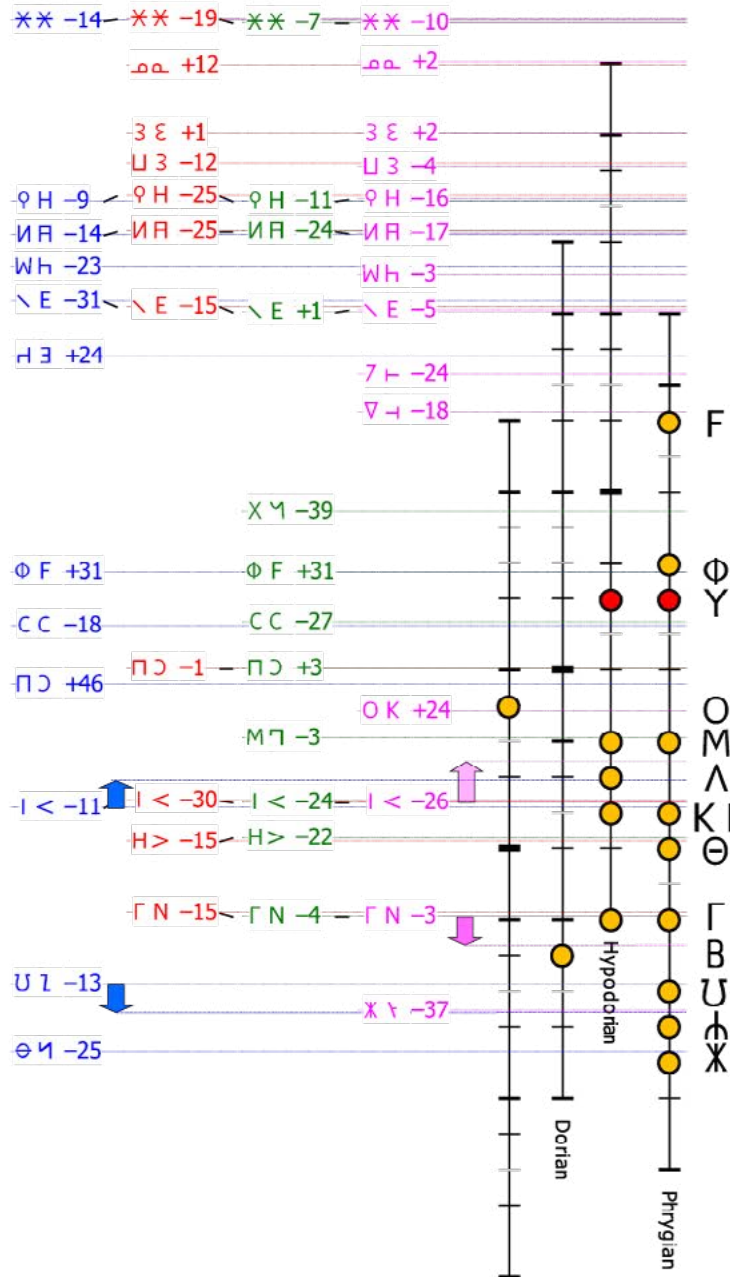


Figure 758: Predicted pitches of the Long Auloi and notes used in the Delphic Paean by Athenaeus (Pöhlmann and West 2001 no 20). Arrows: cross-fingering chimney holes / fully opening teardrop holes.

random from a purely music-theoretical point of view, it would be perfectly motivated from an instrument layout like that of HL, where the little-finger hole would otherwise be wasted. The Hypodorian *pyknón* requires some cross-fingering, while the Phrygian diatonic tetrachord $\text{I}-\Theta-\Gamma-\text{U}$ ($a-b-b-c-d$) mostly relies on standard fingering, with a little down-tuning of the index hole of HL. The absence of Phrygian chromatic in this region in the piece coincides with the lack of a corresponding tonehole on any of the pipes. After all, Aristoxenus reportedly called Phrygian well-suited for diatonic, a notion that may also have informed, or been informed by, the design of other auloi.¹²³ At any rate, the incomplete highest Phrygian tetrachord is necessarily chromatic, because the diatonic alternative note exceeds the reach of

123. Clement of Alexandria, *Strom.* 6.88.1. For the Megara aulos 1965A, see Terzēs and Hagel 2022: 58.

the index fingers. The two lower notes of its *pyknón* are readily provided on HR by the teardrop-shaped thumbhole as well as by fully opening the treble hole on HL, while its top note requires the index of HR. In this way, instrument and melody also share the same upper boundary.

The note **B** (*db*) is of special interest because it appears only once; harmonically, it sort of bridges the gap between Phrygian and the odd “Mixolydian” **O** (*f#*), by interpreting the latter as *gb*, a fifth below **B** (*db*), which in turn stands a fourth above **A** (*ab*). The melodic figure proceeds as follows:

11

8 δά - πε - δον ἄ - θραυσ-τον· ἄ - γί - οἰς δὲ βω - μοι - οἶ - σιν
dá - pe - don á - thraus-ton: ha - gí - ois dè bō - moi - oī - sin

Pöhlmann and West 2001 no 20.11

Notably, **B** (*db*) appears as a brief upward excursion between two instances of **Γ** (*c*) a semitone below. On HL, this amounts to briefly rolling the thumb back on its tip to uncover the edge of the teardrop thumbhole, only to revert immediately to a more comfortable position, with better grip on the instrument. Once more, a melodic choice in the Paean would appear well-motivated on an aulos or set of auloi sharing basic features with the Meroë instruments.

While each of the observed correspondences might be incidental, in total they seem to support an interpretation of the long instruments as representing a genuine Hellenistic musical tradition in which the arts of instrument making, playing and composing were inextricably intertwined. The auloi accompanying the Athenian performance at Delphi, only a century before Amanishakheto’s reign, may have been similar in many respects, even if perhaps not regarding the exuberantly long bass sections. At any rate, we have seen that the choice of the lowest available notes also coincides with documented musical evidence from a Greek score, retrieved from Egypt. Overall, the final and most spectacular pair of instruments confirms their belonging within a globalized music culture whose tonal structures we can understand from Greek texts and scores using a notation that relies on the Greek alphabet.

7.2.3. Handling

As we have seen, each pipe allowed switching between two bass notes, without interrupting the performance, by operating its slider, provided all holes between the little finger and the slider hole were shut. One of these two notes per pipe was fixed, being the slider hole, which consequently played a note of eminent harmonic importance. The other could be preselected using the rotary sleeves. Whenever another hole above the slider was opened in this way, however, the slider became useless.

Apart from the demanding finger span and the difficulty of moving the slider while maintaining an airtight hold on other holes, the main challenges in playing these instruments must have concerned, on the one hand, the considerable air pressure required for making such a long and narrow tube speak,¹²⁴ and on the other, the sheer weight of the pipes. After all, each tube of nearly four feet length needed to be supported by nothing more than the thumb of the playing hand; moreover, since that hand was constrained to the holes closest to the mouth, the long end of the pipe exerted substantial leverage. The resulting forces not only affected the thumb, but perhaps more importantly the mouth of the player, whose teeth and upper lips had to counterbalance the weight of the pipe, the force of which was significantly increased due to the much shorter lever at the mouth side, the reed being relatively close to the pivot provided by the thumb. In addition to the strain put on the teeth and the lips, especially when the latter were bent around the former in order to facilitate controlling the vibration of the reed blades, the ensuing lateral forces exerted on the same vibrating blades must have jeopardized tone production.

124. See ps.-Aristotle, *On Things Heard* 800b: πάντες γὰρ χαλεπῶς πληροῦσι τοὺς βόμβυκας καὶ μετὰ συντομίας πολλῆς διὰ τὸ μῆκος τῆς ἀποστάσεως “For everyone has difficulties filling the (entire) tubes and must put in great effort, because of the large distance.”

The instruments being fully clad in metal and partly containing a core of a relatively dense materials such as bone—also, olive being on the heavier side of available woods—we must wonder whether it was possible to play them at all without additional support. Of course, no known iconography appears to show auloi resting on anything but the performer’s hands, but that might easily be attributed to artistic bias, an understandable aversion to depicting technical compromises instead of the aesthetic ideal. Contrarily, if the feasibility of unsupported performance can be demonstrated, we may be reasonably certain that the ancient players did not use any support.

The discussed vertical forces can all be mitigated by tilting the instrument from a straight horizontal position upward or downward.¹²⁵ At first glance, some depictions appear to show substantial inclination, sometimes almost vertically held instruments—but these are arguably attempts of showing the performer frontally while still indicating the length of the aulos.¹²⁶ Where the artistic setting allowed for a free choice of instrument direction, such as in depictions in profile or in small bronzes, the pipes are shown being held nearly horizontally. After all, any tilt would have to be followed, by and large, by the head in order to accommodate the reeds within the mouth.

Not having a replica in original materials at our disposal, the question of feasibility of unsupported playing could not at present be reviewed in direct experiment. Instead, we can estimate the involved forces with sufficient precision even by a rough calculation. The weights of individual parts can be obtained from their external diameter, the measured or extrapolated bore diameters and the number and thickness of their metal encasings. The following figures are based on assumed densities of 1.5 g/cm³ for bone cores,¹²⁷ 0.98 g/cm³ for olive wood,¹²⁸ and 8.2 g/cm³ for bronze.¹²⁹ Each part was treated as a compound of cylinders, subtracting the fingerholes. For each layer of bronze, a thickness of 0.3 mm was assumed, except on the sturdier slider tubes, where that value was doubled. The mass of the sliders was roughly determined from their lengths and cross-sections, while the volume of the bronze chimneys was taken from a photogrammetric model of part 090, and that of the knobs of rotary sleeves roughly calculated from their triangular or circular shapes. From the resulting masses, the two relevant torques were derived for each part, substituting, in good approximation, centers of gravity by longitudinal centers: one referring to the thumbhole as the pivot, and one for the full extent of the pipe starting from the mouth end. Divided by the distance between mouth end and thumbhole, the latter then gives the force exerted on the thumb, while the former allows us to estimate the pressure of the reed against the upper jaw. The results are detailed in table 5.

Table 5: Estimated forces on thumb and upper jaw when playing the Long Pipes.

	HR	LL	LR	HL
Weight of pipe:	350 g	386 g	361 g	385 g
Thumbhole position from mouth end:	219.0 mm	280.6 mm	285.2 mm	260.8 mm
Force at mouth end:	−0.53 kg	−0.46 kg	−0.36 kg	−0.53 kg
Force at thumb:	0.88 kg	0.84 kg	0.72 kg	0.92 kg

A weight of almost a kilogram on the last joint of the thumb is not negligible but probably manageable. But is it possible to sound a reed that is subjected to a force of half a kilogram? Fortunately, it is relatively easy to design an experiment with the help of one of the currently most widely played aulos replicas. When a weight of 0.5kg is attached to the end of the lower pipe of the Louvre aulos,

125. The effective forces would then equate those in horizontal position times the cosine of the angle of inclination.

126. Of course, three-dimensional representations in brittle material, such as coroplastics or stone figures, where the pipes are often shown running down the chest (e.g., fig. 2.22 above), cannot be counted as evidence for downward-tilted performance either.

127. The species could not be established, but must be sought among grazing mammals. The given density is taken from data for sheep (Campbell et al. 2003).

128. See <https://www.wood-database.com/olive/>, accessed 2024-04-17.

129. See https://www.wermac.org/materials/density_of_metal.html, accessed 2024-04-19: for 8–14% Sn, 7.4–8.9 g/cm³.

the forces at its thumbhole (which sits at half the total length) and mouth end are for all practical purposes identical with the largest predicted for the Long Pipes. The resulting instrument certainly feels unfamiliar and opening the thumbhole takes getting used to, but I have experienced no difficulty in making the reed sound or otherwise manipulating the pipe. Luckily, the effective extension of the Louvre aulos reeds is just as long as the larger predicted lengths for the Long Pipes, so that the experiment is representative also in this respect. Without doubt, on very long instruments it is beneficial to keep the external part of the reed mouthpiece as short as possible, in order not to compromise the seat of the reed in its socket with increasing torque at the entry point. In practice, it must only be ensured that the edges of the flaring reed blades do not touch the walls of the socket, which would prevent their free vibration. Narrower reeds therefore might be pushed further in than wider ones of similar blade length. However, it is unlikely that ancient performers would have opted for reed stems whose cavity was considerably narrower than the 8.5–9 mm of the pipe bore, because larger reed blades generally facilitate the production of bass notes.

7.3. Overblowing

In the context of the shorter instruments, we have considered how overblowing one or even both pipes to the next harmonic mode, a twelfth above the fundamental pitches, may have helped accessing top notes above the highest fingerhole. This seemed especially plausible for the sake of completing the large intervals on the top of chromatic tetrachords on the instruments with wooden cores. For all we see, such a maneuver was not supported by anything like the readily accessible “speaker holes” of modern instruments; possibly, players could destabilize the fundamental oscillations by opening up a small gap for instance at the index-finger hole.

On the other hand, we find five instances of the tiny drilled holes on the bulbs or directly beneath them, which are so well known from other finds and have been identified as the devices that the texts call “*sŷrinx*,” “whistle.” These must normally have been closed with some sort of plug, quite probably a bone pin not unlike those that held the sliders from Megara in place,¹³⁰ secured to the tube with a thread. However, the *sŷrinx* holes on the Megara Aulos 1965 were instead operated by sliders extending toward the region of the thumb, so that they could be opened and closed very fast, without taking the instrument out of the mouth—perhaps even without interrupting the sound? *Sŷrinx* holes with sleeves postdate our find, being attested mostly on instruments from the Vesuvian region. They provide a clean means of sealing the hole without stray parts that might get lost, but are typically situated too far up to be operated in playing position.

The Meroë pipes, in spite of all their technical sophistication, content themselves with simple holes without sleeve or slider. Out of the total of five, four are found on the bulb sections of the Long Pipes—three on the bulbs themselves, and one on the spigot of 135; the corresponding hole in the bronze tube, presumably 130, is lost. Curiously, this single low-positioned *sŷrinx* is associated with a high pipe, an anomaly that has so far defied explanation. Judging purely from the physical effect of a speaker hole, we would expect one to be optimally situated at about a third of the distance between the tip of the reed and the tonehole region whose fundamental oscillation it is primarily supposed to disrupt.¹³¹ As a consequence, a lower speaker hole should mean that it was more typically activated for lower notes. This does not help, however: while the three *sŷrinx* holes in the bulbs occupy a meaningful position for raising the notes from the fingerholes by a twelfth, thrice the distance to that in 135 takes us right to the slider tube, a region without any holes. Did this *sŷrinx* target the bass holes to a greater degree than the others? Unless the proposed reconstruction is flawed altogether, this question must be deferred to future experiments.

130. Terzēs and Hagel 2022: 24; 28 with 76–77 pl. 8–9.

131. Hagel 2012b: 498–99.



Figure 7.59: Fibers on the spigot of bulb 064 (with reed-socket cone 223 over bone core 110).

The last *sŷrinx* is found on 116–139, going through the wall of the former and the spigot of the latter. Above, these parts were assigned to one of the two lower pipes in the set of the two shorter instruments with mechanism. Here we appear to find four related pipes, only one of which bears a *sŷrinx* hole, so that the option of consistently overblowing both pipes of a pair at once seems precluded: when the *sŷrinx* was activated, the instrument, unless played as a *mónaulos*, would fall apart in a “piping” and a “whistling” component.¹³² It is hardly a coincidence that the same general configuration is observed on the four “Silver Pipes” from Pompeii: only one of them sports a *sŷrinx*, which also goes through the bulb spigot; here as well, the respective pipe is one of the two lower pipes and has the knobs of its rotary sleeves on the left side.

In contrast to the Pompeii instruments, though, this *sŷrinx* from Meroë is no more equipped with a sleeve than those on the Long Pipes. Was it stopped with a pin, as we must assume the others were? Its position on the spigot might suggest another method: if it was not glued in place, one might also close and open the hole by rotating the bulb in its metal socket. Yet this would be less practical than might at first appear. First, a rotation of the bulb would also change the orientation of the reed blades in relation to the finger holes; this would require rotating either the reed cone with the reed in the other direction, if it was not firmly connected with the bulb, or the reed inside its socket, if it was. Second, a tight fit between bulb and tube was evidently ensured by windings of fine flax around the bone spigot (see fig. 7.59). Moving it would always risk displacing the fibers, with the hazard that they would get in the way of the *sŷrinx* itself, blocking the hole and disrupting its function. Finally, as long as air tightness depended on those fibers in the first place, it is unclear how it could be maintained around the *sŷrinx* hole. Any form of winding that spared the hole out would inevitably also open a channel from it in both directions, which would connect the external hole with that in the bone even when they would not directly coincide. With the ensuing leakage, lower notes would be increasingly dimmed and difficult or impossible to produce. On balance, it is therefore far more likely that some sort of plug was used on this pipe as well.

7.4. Production and Destruction

7.4.1. Tuning

Apart from the technical challenges that the Long Auloi shared with other types, and the additional task of producing a workable slider, these instruments appear to transgress the boundaries of known aulos technology in a fundamental point: their bores deviate markedly, and apparently intentionally, from a smooth cylindrical shape. Compared to similar-looking instruments with cylindrical bore, this causes significantly different pitches for similarly located toneholes. Above, we have struggled to predict intended pitches where substantial parts of the bore are lost. With ancient means, it would have been impossible to foretell the consequences of bore variation on the intonation even when it was fully known. Much the same goes for the effects of the chimneys.

132. See Hagel 2012b: 511–13.

How, then, were these instruments tuned in the first place? After all, while players can bend high notes to the required pitch, the same is not true for remote bass toneholes, where an identical change of effective reed length by skillful manipulation becomes negligible compared to the long stretch of tubing in between. At least the bass notes must therefore have been tuned with precision.

The pitch differences caused by bore variation are too large to be balanced simply by gradually enlarging individual toneholes until they played the intended pitch. We must therefore posit a more elaborate procedure, presumably starting from functioning prototypes and involving gradual adjustments not only of hole size but also of the bore diameters of individual parts. This entails a slow and painstaking progress from the mouth end downward, since holes sufficiently removed further down the tube hardly influence the pitch of their higher companions, while adjustments higher up the tube always affect the intonation of each and every lower note. In the case of the chimneys, whose heights vary and seem finely adjusted to their individual purposes, some experimenting may have been required, possibly involving various chimney models of clay or wood. At each step, the makers would have had to check on the pitches and intervals, applying a suitable reed. This, in turn, required, either some tool that sounded a reference pitch and a fine ear to set the other note at according intervals, or perhaps a whole set of reference pitches that the instrument under construction was meant to play.¹³³ Since reed instruments would not produce steady notes, tubes blown as (end-blown) flutes are likely candidates, perhaps aligned in the manner of panpipes. These would also ensure that sets of instruments were able to play in harmony even when produced at different times.

7.4.2. Adjusting

Due to varying finger lengths and other factors, individual players might prefer different relative positions of fingerholes regarding their lateral placements (“azimuths”), which do not affect the pitches. Such adjustments would almost certainly require the presence of the customer in the workshop. To keep the respective time to a minimum, it would doubtlessly be beneficial to limit this stage of interaction to the final steps of assembly, as far as possible. This may explain the otherwise puzzling observation that, while the makers of the Meroë instruments were perfectly capable of producing bronze tubing of more than 27 cm and fit it over a wooden core, most of the bodies of W1 and W2, the short pipes without mechanism, consists of much shorter sections, often with only a single tonehole. The thumbholes, in contrast, are always paired with at least one other hole—the index hole on the wood-core lengths of L-HL and L-HR, middle-finger hole and index hole on W2, and probably the middle-finger hole on W1-L. This may continue the old tradition of bone auloi, whose makers were considerate enough to assist modern reconstruction efforts by producing “central” sections with three or four holes that regularly include the thumbhole. Indeed, it is the little finger, and to a lesser extent, the ring finger, that require individual adaptation the most; in extreme cases, also the index, which the instruments from the Oxus temple typically separate from the thumbhole section.

If the parts were produced individually, ready for assemblage, each would have to come with its own wooden core. The numbers of core and encasing sections would thus be identical, and the respective boundaries would either coincide or be offset for better stability, albeit by a comparatively small amount. At any rate, such a construction appears also inevitable wherever the outer bronze tubes were themselves connected by a thin internal ring. This ring, soldered to the interior of the ends, locally reduced the diameter and would thus have prevented fitting a longer core across the meeting point of the metal tubes. Instead, the reduction would have to be lathed into the end of one or both of the core sections that were fitted together in this way.

Notably, if the thin rings were firmly soldered not only to one side of the joint, while the other was merely pushed over it, but to both meeting tube ends, extreme caution would have been needed not to char the wooden core in the process. Quite probably, a eutectic lead-tin solder would have been required which would liquefy at temperatures significantly below 250°C.

133. For potential references to pitch pipes in antiquity (*epitónion*, *tonarium*), see West 1992: 113–14.

7.4.3. Detachable Sections

Modern wind instruments often come in detachable pieces, facilitating transport as well as cleaning. Was this also an option for ancient auloi, and especially for the Long Pipes, transporting which must have posed an extraordinary challenge? In the shorter pipes, nothing seems to intimate such an assumption, apart from the fibers found around the spigot of bulb 064 (fig. 7.59 above; see ch. 6.8), which appear to indicate that this bulb, and therefore potentially all the bulbs, may have been detachable. On the Long Pipes, the peculiar connection between slider tube 085 and section 072 by a sturdy metal ring joining two metal spigots would doubtless encourage an interpretation as a nonpermanent junction. But it is unique and, more importantly, located at a wholly unlikely place: were the tube disassembled at this point, the slider would still stick out from the lower part, diminishing the advantages of disassembling while itself becoming much more vulnerable to damage. Detachable joints above the sections with the slider holes are therefore unlikely. However, it may well have been possible to remove the long end parts below that section.

7.4.4. Destruction

If the proposed reconstructions are correct, they can also help understanding the destruction process that preceded the burial of the instruments. On the two excavation photographs, longer stretches of contiguous sections can hardly be found—the few there are mostly concern the sturdy bone-core bass parts of the Long Pipes. Admittedly, the photographs have not been taken of an entirely undisturbed cache; at least the detached slider part 051 was moved between the two shots. However, hardly any of the visible tube fragments can have been displaced at that point, given their embedding in the soil and within each other.

Unfortunately, only a small part of the find is discernable on the images, so that it becomes impossible to trace longer stretches of the individual tubes. Only in one case can we identify detached sections that seem once to have been contiguous. They come from the lower half of S1–H; one comprises parts 023 and 078, the other, 103 and 069 (fig. 7.60). Though their orientation is preserved—a one to one chance, after all—the two sections have become widely separated in the ground. Moreover, 069 extends to the edge of the space that contained the find, so it must have been detached from the next part, as well, before being laid down. Consequently, at least in this case the pipe had been broken down to fragments as short as 9 cm—clearly much shorter than would have been necessary only to fit the pieces into the space. The destruction process was therefore not motivated by purely practical reasons, but may have involved the idea of ritually silencing the instruments and/or banishing their spirits.¹³⁴ This notion is supported by the comparatively wide separation of once contiguous parts, an impression that is reinforced by the sheer fact that instead of showing potential members of similar instruments grouped, the photographs appear to display a wild medley of incongruous sections. The instruments, instead of being broken and deposited one by one right at the site, appear rather to have been brought there already as a bundle of pieces.

7.5. Summary

Already on the basis of purely external criteria it had become obvious that the instrument find from Amanishakheto's burial contained three types of aulos, each represented by four pipes forming two instruments. A careful reconstruction, even though not unequivocal in every detail, not only confirmed this, but associated each type with a typical length, and above all, a particular musical style. The long instruments—with about 115 cm more than twice as long than the others on average—appear to be designed for the kind of music we find notated on stone and papyri in the Hellenistic period. Their tonality revolves around Lydian, Phrygian, and Dorian, and generally the canonical seven keys that were later associated with “orchestic” music. Technically they are the most elaborate, with their intricately crafted sliders, their inclined side tubes, and the abundance of bass holes, round and rectangular, on two of them. These instruments also represent a hitherto unknown type regarding the fixed hand positions on

134. See Sánchez Muñoz 2023 on the much earlier Silver Pipes from Ur.



Figure 7.60: The distribution of successive parts of S1-H in the find.

simple fingerholes on the top, despite the many rotary sleeves further down the tubes. In this respect, they may be regarded as developing a tradition known from the auloi found in Megara.

In contrast, the shortest instruments have no mechanisms at all; at one point, the choice between two harmonic options may have been determined by a simple plug. Unlike all published aulos finds so far, these are chromatic instruments in the ancient sense, prominently featuring sequences of two semitones at intervals of fourths or fifths. Although possibly intended to perform together, they seem to defy the system of keys, being tuned only within themselves.

The remaining two instruments appear much more familiar, resembling auloi found around Pompeii and, more fragmentary, elsewhere. Being equipped with rotary sleeves throughout and sometimes including alternative thumbholes, they are designed for variable hand positions as well as switching between different keys. In stark contrast to the Long Pipes, their tonality leans toward the “sharp” keys such as Iastian, as abound in Roman Imperial scores. Apart from convenient diatonic options, a triple-switching sleeve on one of these pipes unmistakably defines a chromatic scale—surprisingly one that we otherwise find in musical cosmology as the pitches emitted by the revolving planetary spheres.

Belonging to three very distinct kinds of music and apparently slightly different tuning standards, it seems that, even though the instruments of the same kind may have been designed to perform together, a common performance of all six would not have been feasible harmonically. Pairs of players may rather have taken turns in performing, be it in the course of the burial ceremony of the deceased Queen or, during her reign, at official occasions or for more private entertainment.

Nonetheless the four instruments with mechanism, at least, disclose their adherence to the same heritage. Perhaps most instructive is the status of $\Theta\upsilon$ (e'), which corresponds to the highest note ($n\acute{e}t\bar{e}$) on the kithara. Both sets employ it as a treble note, but in different ways. On the low-pitched long instruments it is the highest note overall, present only on L-HR. In contrast, it is found on all four of the shorter pipes, forming the treble note of the lower members of each pair.

7.6. Naming the Instruments?

Ancient texts preserve numerous terms for various kinds of aulos. Sometimes we get brief hints at their characteristics, sometimes we are left to guessing based on the semantics of a name, and sometimes a term remains obscure. The best-known designations come from Roman-period learned texts with antiquarian interests, such as Athenaeus’s *Deipnosophists* or Julius Pollux’s *Onomasticon*, both

composed by authors from Egypt. These literary attestations are augmented by a couple of papyri from Alexandria, dating from 13 BCE and therefore contemporaneous with the Meroë instruments.¹³⁵ In the frame of a contract about a year-long aulos training for the slave Narcissus, they detail more than twenty-five pieces he would learn to play, on at least seven different instruments.

Given the chronological and geographic proximity of find and texts, one might expect that the types of instruments contained in the former are at least partially reflected in the latter. On the other hand, the social gap between an Alexandrian slave piper, albeit maintained by a truly wealthy owner, and what may have been official performers for the queen of a mighty empire might caution us from identifying the instruments or repertoire of the two too rashly. At any rate, both the chromatic simple instruments and the lustrous slider pipes appear to resist an association with ancient terms. Even though the latter seem well-suited for the kind of Hellenistic music that revolved around the Phrygian key, they may not form a “phrygiaulic” instrument as mentioned in the contract or the “Phrygian aulos” of other sources: many scholars would rather reserve that term for pairs where one pipe ended in an upward-curved “horn,” best known from the cult of the Great Mother.¹³⁶ The chromatic instruments, on the other hand, even though the shortest in the set and arguably the most threnodic, come nowhere close to the length of a mere “span” reported for the Phoenician-Carian pipes called something like “*gíngroi*” and mentioned not only as mournful but as typical beginner’s auloi.¹³⁷

It is only the intermediate instruments that might fall in a well-attested category. As we have seen, their shared tonehole range spans the same ninth from ΦF (*D*) to $\Theta \mathcal{N}$ (*e'*) that forms the typical ambitus of the ancient cithara. Three of the four pipes furthermore include ΦF (*D*) as a “vent hole” without a rotary sleeve, indicating that this bass note of the cithara was also the lowest note typically employed on these auloi, musically disregarding the remaining physical extension to the pipe exits. At the same time, their available pitches enabled playing in the keys Bellermann’s Anonymus reports for the cithara: Lydian, Hypolydian, Hyperastian and Iastian (in addition to Hypophrygian and Phrygian on S2-H), and S1-L specially supports the single chromatic *pyknón* in Ptolemy’s cithara tunings. These instruments are therefore excellent candidates for the well-attested “*auloi kitharistérioi*,” a term that was already established in the fourth century,¹³⁸ but is also found in the Alexandrian contract, where it appears associated with the supreme deity of Ptolemaic Egypt in the special form of “Serapian *kitharistérioi*.”

The last assignment for Narcissus are two instrumental pieces, to be played “on left-hand [pipes].” The idea of pairing two pipes that would normally be assigned to the same hand is also found in production notes (*Didascalía*) to comedies by Terence: two of these are reported to have been accompanied by “two right-hand pipes.”¹³⁹ Any such combination of similarly handed pipes of course requires having two regular pairs at one’s disposal, just as the Meroë find comprises two pairs of each general type of instrument. However, not all three types would lend themselves to such divergent recombination. Among the long instruments, it would be plainly impossible to play one of the high members with the “wrong” hand, due to the outward-pointing position of their little-finger holes, and at least highly impractical to do so with one of the low pipes, whose index holes are displaced toward the playing hand. Similarly, the lateral secondary index hole on W1-H inevitably assigns the pipe to its hand, and the same is probably true for the position of the little-finger holes on all other three. The short pipes with rotary sleeves, in contrast, show no similar restrictions. Despite comparatively small lateral hole displacements for easier handling, each of these can be operated by both hands, even though, when pairing either two left-handed or two right-handed pipes, the knobs would point toward the palm of one hand, but away from it on the other.

135. Papyri Berlin 13057R and 13049R2; see Bélis and Delattre 1993; Claytor 2024: 305–6.

136. On the “Phrygian aulos,” see Bélis 1986 (but see Hagel 2009a: 412 n. 107).

137. Athenaeus, *Deipnosophists* 4.174f; Julius Pollux, *Onomasticon* 4.76; Hesychius s.v. γιγγρίαί.

138. Quoted for Aristoxenus (Athenaeus, *Deipnosophists* 14.634f; see also 4.176f), Ephorus, Euphranor, and Alexis (4.182c). Julius Pollux explains the term: κιθαριστήριοι δὲ καὶ τοῦνομα διότι κιθάραις προσηύλουν διδάσκει (4.81). “That the citharistic [auloi] accompanied citharas is already taught by their name.” Note that this statement does not prove that Pollux was familiar with the instrument or that his explanation is necessarily correct.

139. *Heautontimorumenos* and *Eunuchus*: “*tibiis duabus dextris*.” For the intractable problems concerning the incongruence between the *Didascalía* and Donatus’s commentaries, see Moore 2012: 56–63. The papyrus’ (which Moore does not cite) two left pipes add credibility to Donatus’s “similar right or left pipes” (*tibiis paribus dextris vel sinistris*) in his preface to *Andria*.

From the limited evidence the Meroë find offers, we can preliminarily observe that the only instruments potentially designed for left-left or right-right pairing are those that conform most closely with the range of the cithara and to the musical documents from the Roman period.

7.7. Methodological Considerations

While the foregoing discussion tried to flag different degrees of certainty regarding reconstruction and interpretation, it may be beneficial to add a few considerations about the broader picture. On the one hand, deep structural affinities between the Meroë auloi and other known finds as well as reconstructions of various stages of ancient harmonic systems from texts and surviving melody fragments appear to lend significant credibility to many of the conclusions reached above. On the other hand, it must be noted that both the interpretations of other aulos finds and the reconstruction of most technical respects of ancient harmonics have been proposed by the present author. In order to assess potential flaws caused by circular reasoning and bias, the reader would therefore have to delve not only in the technical minutiae of the preceding pages, but closely study hundreds of others, often full of dense argument and not in all cases readily accessible even in a bibliographical sense. Moreover, not the least part of our science relies on a knowledge of Ancient Greek far beyond basic grammar, a knowledge that has more and more become the privilege of a minority even within classical studies.

It is not the aim of this short chapter to disperse any doubts, least of all those that have repeatedly been raised above. But it may be worthwhile to share a few details from the reconstruction process, which developed between intense weeks in the Museum and digesting data without immediate access to the material in the course of nine years, including the disruption of a planet-wide pandemic. While a survey of sleeves, thumbholes, sliders and diameters had almost immediately suggested the number of instruments involved as well as the existence of three basic types, and the association of the multiholed bass sections with the long pipes had emerged not long after, the following six years had been filled with the search for a detailed “theory of everything,” developing, testing, and disproving innumerable design hypotheses, while at the same time refining the methodology, keeping the software up to new requirements, so that results that would have taken a day to obtain became accessible in a few moments, and patiently enlarging the basis of any reconstruction attempt by joining further splinters and identifying further pieces in the old photographs. Often breakthroughs became possible only by eventually discarding long-cherished hypotheses, such as that one of the three chimneys belonged on a section from the “wooden” instruments, or more generally, that the fingered regions of the long pipes, and especially their higher members, were more similar than they now seem to have been. By a stunning coincidence, during the very moments when I finally started to look for a home for the newly orphaned chimney, Susanne Gänsicke announced she had attached another chunk to a fragmented section and it now appeared to show the unmistakable traces of chimney solder, so that several pieces fell in place at once.

At one earlier point, an integral solution for the slider pipes had already appeared in reach. On close inspection, however, a mismatch of 2 mm remained unaccountable for—only half a percent of the respective slider’s length, but more than could be neglected in good faith. Only late it turned out that progress in that respect had been held back by the seemingly natural interpretation of 034 as a dolphin hole, until the addition of a tiny part showed that it contrarily contains index and thumbhole of L-HL and thus provided a section that had been considered fragmented beyond recovery.

Especially difficult to overcome was the conviction that every aulos should come with a thumbhole. For years, I had thus looked for indications of one on the underside of 015, until finally accepting that this part instead featured an additional lateral hole for the index finger. This case had at least not greatly influenced the predicted pitches, but it once more highlights the difficulty to appreciate diversity in fragmentary evidence.

It is especially such stories of fettering error and final resolve by new evidence that I hope will lend some credibility to the present reconstructions: obviously, neither bias nor circular reasoning helped

shaping a robust hypothesis as long as some convictions had not been overcome that, as eventually became clear, had been running contrary to the evidence.

Another, less humiliating indication of methodological reliability regards successful predictions. When evaluating a finite body of evidence like in the case of the Meroë find, such predictions are naturally only possible where one had before not looked closely enough. The reconstruction of S1-H involved such a case, when the musical evaluation demanded a spacer ring of about 7 mm between 078 and 103, which could then be located on the excavation photograph. The most intricate example however concerns the complex part 043 with its multiple holes within a single rotary sleeve, including a shifting thumbhole. For many years, one of the internal holes had escaped everybody's attention. As a consequence, the piece appeared to make no technical sense unless followed by at least two more finger holes above it. When the reconstruction of ever larger parts of S1 and S2 became established with increasing confidence, however, it emerged that there would be neither space nor the required parts for such high fingerholes. At some point, logic demanded to reassess the structure of 043—more particularly, to look for another internal hole that would open up another thumbhole in the section's alternative state, which then duly turned up at the predicted position. Again, since these predictions were not hinged upon some small local question but involved the overall reconstruction of an entire set of related instruments, they may, when it is judged, intercede on behalf of its general reliability.

Again, all this is not to imply that the proposed reconstitution of six instruments demands authoritative status. Doubt might, for instance, be shed on the arrangement of the elusively corroded constituents of W1-L, whose current reconstruction largely rests on the idea of maximizing common pitches with its supposed mate, W1-H. Overall, though, we may harbor some confidence that any potential local rearrangements would not change the large picture, nor the general musical interpretation of the three sets of instruments.

7.8. Summary of Proposed Arrangements

The following lists communicate the instrument designs as reconstructed above (see also figs. 7.61, 7.62, and 7.63). While the bulk of the parts is precisely defined regarding placement and orientation, some of the reed cones are exchangeable between the pipes of one instrument—and might even have been so in antiquity.

The instruments are imagined with their exits at the left side and their mouth ends at the right side, so that the sequence of parts accords with the reading direction. The orientation of individual parts is indicated by placing the numbers next to hyphens, according to whether the number tags on the items are attached on their “left” or “right” sides (e.g., “-092” means that part 092 is to be placed with its number label toward the right side).

Pipes are identified by their accession numbers as well as the sigla used above. Permanent assemblages are enclosed in angular brackets, with their identifying part numbers printed in bold; their orientation follows from the enumeration of their parts.

Plus signs are used wherever some part belongs along another item (as opposed to in succession), such as do chimneys and sliders.

24.3578 = HR: -092 | [**003**-010] | -022 | -209 | -227 | -150 | -050 | [166-086] | 100-+149 | 131-+065 | 039- | 102- | 138- | 112 | 225
24.3579 = LL: [**008**-005-024] | [**001**-095-071-099] | 142- | -007+052 | 085- | 072- | -028 | 017- | -136 | 118
24.3580 = LR: -049 | 047-046 | 200- | -027 | -036+053 | 121- | -077 | 076- | -006 | 063- | 137- | 108-
24.3581 = HL: -033 | -026 | [087-096-098-009-**041**] | 206 | [094-097-**029**] | 061- | -032+117+054 | 089-+090 | -034 | 130- | 135- | 106-



Figure 7.61: Proposed arrangement of pipes HR, LL, LR, and HL (top to bottom). Photograph © Museum of Fine Arts, Boston (SC492114).



Figure 7.62: Proposed arrangement of pipes S1-H, S1-L, S2-H, and S2-L (top to bottom). Photograph © Museum of Fine Arts, Boston (SC480514).



Figure 7.63: Proposed arrangement of pipes W1-H, W1-L, W2-H, and W2-L (top to bottom). Photograph © Museum of Fine Arts, Boston (SC480519).

24.3582 = S1-H: -123 | -030 | [023-078] | 231 | [103-069] | 203 | 070- | -057 | -048 | 019- | 134- | 038

24.3583 = S1-L: -037 | 031- | -040 | 144- | 232 | 115- | 043- | 204 | -119 | -066 | 111- | 110

24.3584 = S2-H: -116 | -145 | -101 | -062 | -002 | [114-004] | -020 | -075 | -104 | -068 | 083- | -140 | 160

24.3585 = S2-L: -125 | -132 | -044 | -088 | [079-080-067] | -210 | 126 | 011- | -013 | 016 | 139 | 223

24.3586 = W1-H: -091 | 084- | -014 | 015- | -018 | 156 | 161

24.3587 = W1-L: -025 | 113- | 105- | 021- | -109 | 074- | 148 | 159

24.3588 = W2-H: -120 | -081 | 060- | 059- | -012 | 157- | 158

24.3589 = W2-L: -107 | 133- | -042 | -045 | 073- | -035 | 064 | 146

8 Garstang's Auloi

Stefan Hagel

Six years before the sensational aulos find that forms the topic of this book, Thomas Lea Southgate published a much smaller set of fragments that John Garstang had retrieved from the city of Meroë. The thirty-four pieces described by him had been mounted on a wooden frame and displayed in the “Museum of the Institute of Archaeology attached to the University of Liverpool” (see fig. 8.1).¹ Garstang did not publish or even mention the find, but its significance for understanding the far-reaching connections of Meroë’s music culture was recognized half a century later in connection with the statue of an aulos-player found in the city. Locally produced from sandstone, the “player has been painted pink or flesh colour, and his instrument yellow.”² The yellow was almost certainly meant to reflect a metal encasing; the portion with bulbs, which we would expect to have been white, has perished.³

Unfortunately, the objects can no longer be located by what has now become the “Garstang Museum,” and their existence seems to have faded from the University’s memory. All that remains is a heavily rasterized black-and-white photo in Southgate’s article and his description.

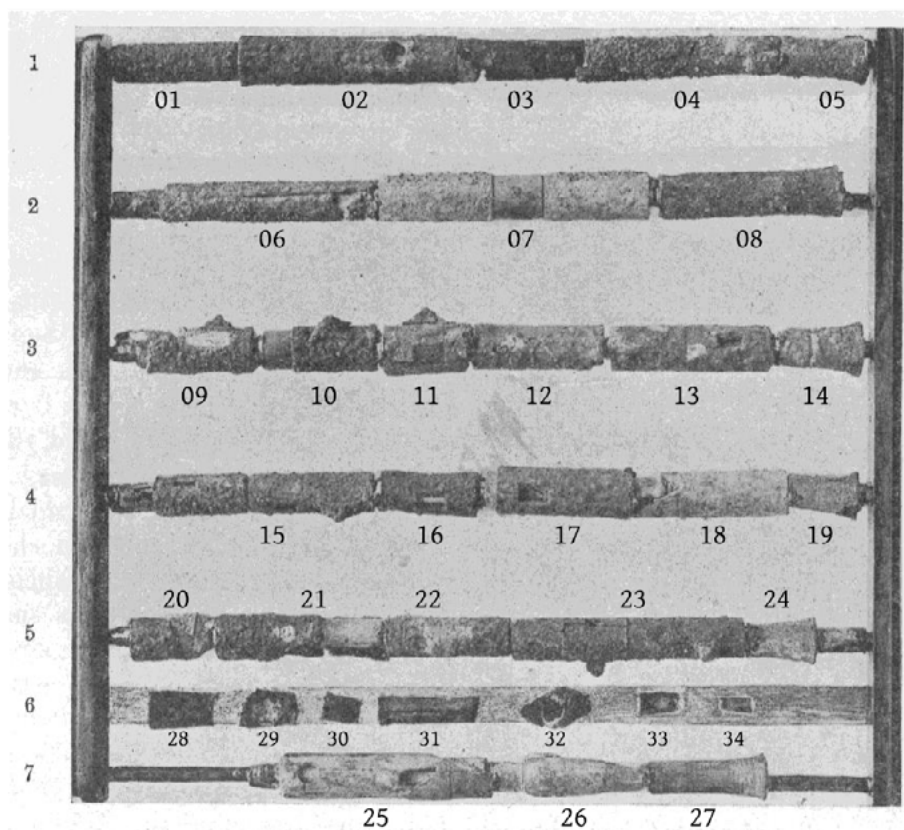


Figure 8.1: The aulos fragments found by J. Garstang in Meroë. Southgate 1915, fig. 1, with added item numbers.

1. Southgate 1915: 21.

2. Dixon and Wachsmann 1964.

3. The apparent coloration of the player’s skin, if identified correctly, may stand in an interesting contrast to his hairstyle, which would not on a first glance flag a northern provenance of this performer.

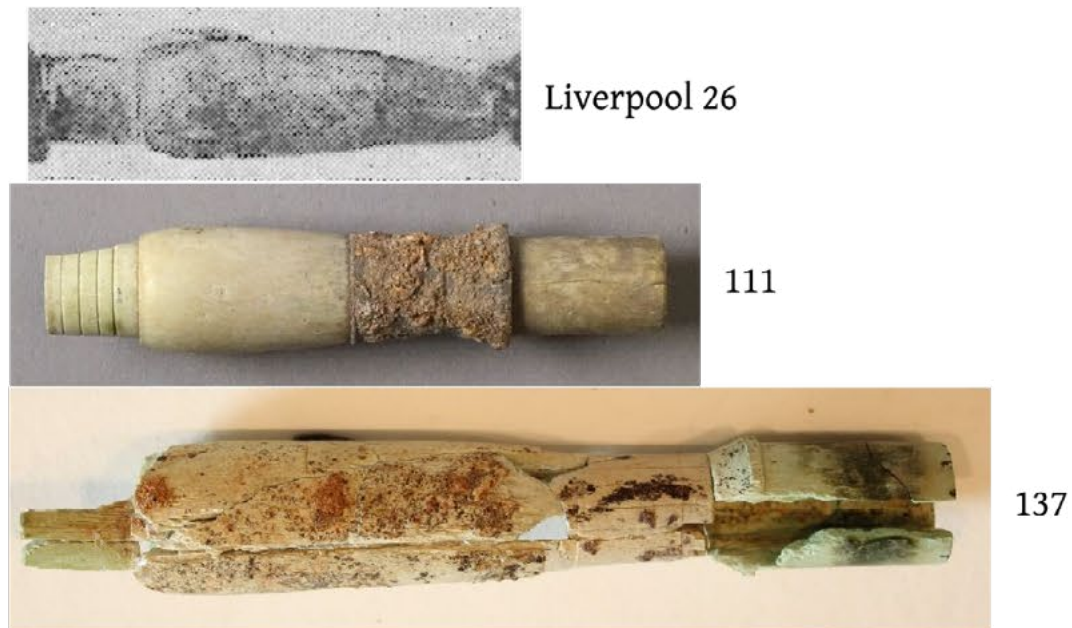


Figure 8.2: Liverpool 26 compared with a bulb from the short (111) and the long (137) pipes from Amanishakheto's burial, all to scale.

“Judging from the slightly conical outlet pieces preserved,” Southgate concluded, “the Meroe fragments indicate five instruments, but there may have been more now broken up and perished” (p. 14). Like Bodley after him, Southgate apparently mistook reed-socket cones for bells (fig. 8.1, items 05, 14, 19, and 24). True end pieces are seemingly only found in items 08 and 27. Southgate’s reported internal diameters, “seven-sixteenths to ten-sixteenths of an inch” (14), that is about 11–16 mm, betray that some of the items had lost their core, which may sometimes have consisted of wood—unless, perhaps, the nearly 16 mm refer only to the very ends of the reed sockets. Southgate also implies varying external diameters, without going into detail (p. 13).

The upper end of his diameters for round toneholes, allegedly 8–11 mm (p. 14: “five-sixteenths to seven-sixteenths”), appears excessive, while his rectangular holes, 8×3 –6.5 mm (“five-sixteenths long by two-sixteenths to four-sixteenths in breadth”) seem partly too narrow; perhaps he measured only the remaining opening of some hole that was partially closed by its rotary sleeve? The diameters for the single teardrop-shaped hole, in item 25, about 12.5×5 mm (“eight sixteenths long, and three-sixteenths at the rounder head”), are credible. Extrapolating from this hole, the body of the respective piece appears to measure 70 mm. This is confirmed by extrapolation from the frame size. Southgate asserts that “[t]he fragments of the five examples shown in the frame are placed together to make up an [sic] uniform length of about ten inches” (p. 18). He must be referring to the five pieces on the uppermost rod, which cover that rod from end to end. Consequently, it is probable that whoever made the frame designed it with a clearance of nicely round ten inches. On this basis, the length of item 25 is also estimated as 70 mm. It appears, therefore, that we should be able to assess the dimensions of the thirty-four items within a comparatively small margin of error (see the attached catalogue).

Much like the instruments from Amanishakheto’s tomb, the cache contains relatively narrow tubing of hardly more than 14 mm as well as wider parts of 15.5–16 mm diameter. Only a single bulb survives (26), though it lacks its lower end. The darker shade that can be observed on its lower third, up to a slight but sharp step, may result from a layer of silver such as decorated the respective area on most bulbs from Meroë. The bulb’s overall dimensions resemble those of the narrower, shorter pipes from the tomb (fig. 8.2); it should therefore belong with the narrower pieces. Similarly, the four reed cones, which may well form two pairs (05+14; 19+24), are also reminiscent of the narrower pipes (fig. 8.3, items 223 and 160). Even though 05 and 14 are a few millimeters larger, they come not even close to the massive cones of the long pipes, such as 106.

With four reed cones that very probably belonged to two slender instruments and a collection of wider tubes, we are therefore dealing with the remnants of at least three auloi, represented by the remains of at least five pipes (accidentally confirming Southgate's count).

The wider pieces reveal another striking parallel to the find from the pyramid: section 02 exhibits traces of a “chimney,” with identical disposition of solder residues around a large tonehole as found on the long pipes (fig. 8.4). We also encounter the same two kinds of knobs in both caches, ring-shaped ones (23) and more frequently those triangular ones (09, 10, 11, 15) that so far distinguish the finds from Meroë.

All this leaves little room for doubt that the doublepipes from both locations ultimately hail from the same producer and may have been played by the same musicians. But they were not the same kinds of instruments. Most strikingly, Garstang's fragments include rectangular toneholes not only on wide (11, 13, 17) but also on narrow tubes (15, 16), which makes the latter part of entirely different instruments than were the narrow pipes from the pyramid. Furthermore, some section types that invariably had wooden cores in the auloi from the tomb are here exemplified as bone cores: this regards a slender bell (27) as well as a section from a wide right-hand pipe with a teardrop-shaped fingerhole, presumably for the middle finger (25).⁴ We must conclude that despite the great number of instruments that were buried in front of the queen's grave chamber, these did not represent all aulos types that existed in the city. Instead, they may comprise a selection whose music was deemed appropriate for the occasion, while others with unsuitable musical connotations may have been excluded.

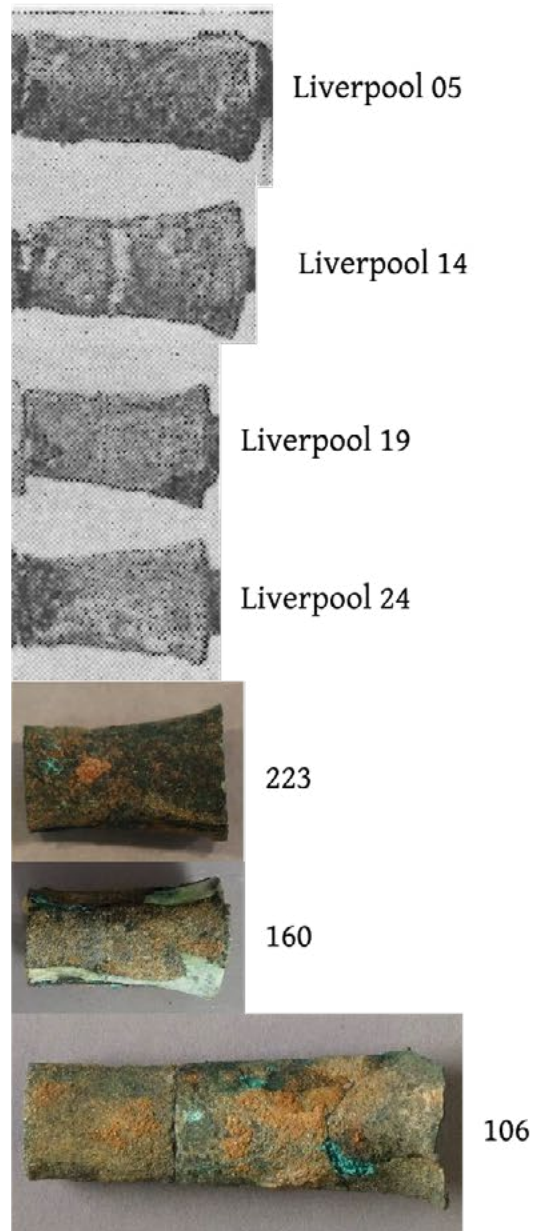


Figure 8.3: Comparison of reed cones from Meroë city and Amanishakheto's burial, to scale.

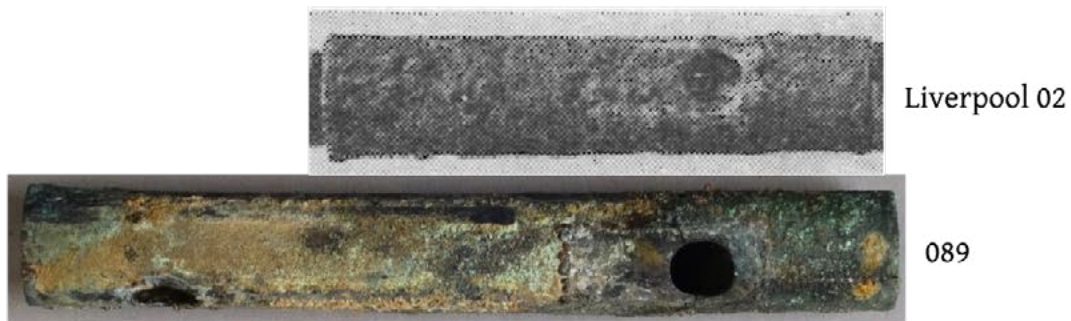


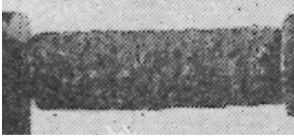
Figure 8.4: “Chimney” soldering traces on 02 from Meroë city and 089 from Amanishakheto's burial.

4. It may have been generally difficult to source bones that would accommodate the flare of such an end section—except for very narrow instruments, where the flare would not much exceed the diameter of more typical pipes. Among the finds from the Vesuvian area, we also find only a single bone bell, and this also belongs to the narrowest aulos (Wyslucha-Hagel 2025).

Catalogue of the Liverpool Fragments

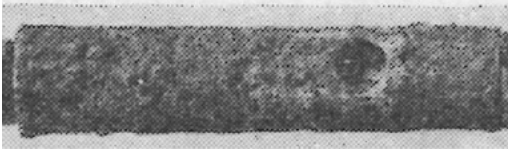
01

Lng≈42, Do≈13.5



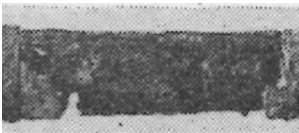
02

Lng≈72.8, Do≈16, H1Pos≈52, H1Dl≈8, H1Dt≈7.5



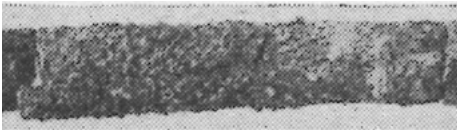
03

Lng≈42.5, Do≈13.5, H1Pos≈8.7, H1Dl≈6.5, H1Dt≈5.7, H2Pos≈27.5, H2Dl≈6, H2Dt≈5



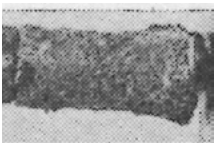
04

Lng≈65.4, Do≈13.5



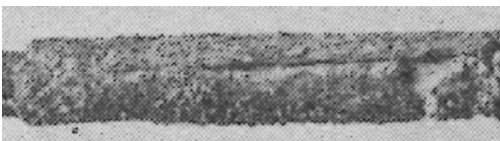
05

Lng≈30.2, Do≈13.3–17.5



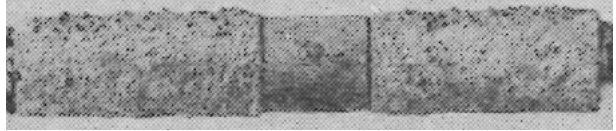
06

Lng≈71.5, Do≈13.5



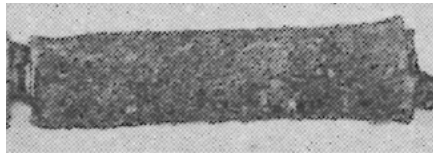
07

Lng≈90.7, Do≈15.5, Sct1≈38.5, Sct2≈55



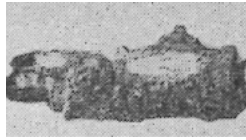
08

Lng≈62, Do≈17.7–14.7



09

Lng≈35, Do≈14.7, H1BS=T



10

Lng≈38.3, Do≈15.2, H1BS=T



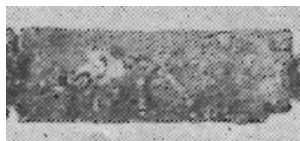
11

Lng≈30, Do≈15.6, H1Pos≈15, H1Dl≈10, H1Dt≈6.3, H1S=R, H1BS=T



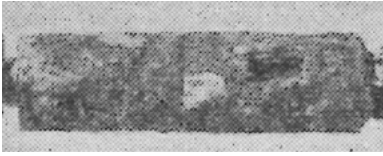
12

Lng≈43, Do≈14.7



13

Lng \approx 54.6, Do \approx 15.5, H1Pos \approx 40.4, H1Dl \approx 8.3, H1Dt \approx 4.4, H1S=R, Sct1 \approx 25.5



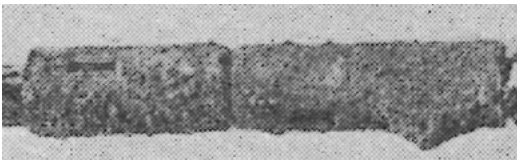
14

Lng \approx 28.5, Do \approx 13.5–18.2



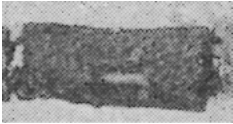
15

Lng \approx 73.8, Do \approx 13.5, H1Pos \approx 10.3, H1Dl \approx 7.4, H1Dt \approx 4, H1S=R, H2Pos \approx 44.4, H2Dl \approx 7, H2Dt \approx 4, H2Az \approx 90, H2S=R, H3S=R, H3BS=T, Sct1 \approx 31., Sct2 \approx 49.8



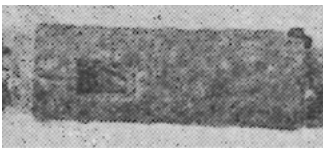
16

Lng \approx 33, Do \approx 14.3, H1Pos \approx 17.3, H1Dl \approx 8.3, H1Dt \approx 5, H1S=R



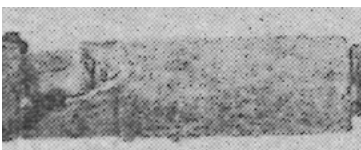
17

Lng \approx 46, Do \approx 16, H1Pos \approx 12.4, H1Dl \approx 9.4, H1Dt \approx 5.4, H1S=R



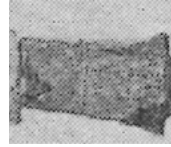
18

Lng \approx 51.5, Do \approx 15.3



19

Lng \approx 24, Do \approx 11.9–16.3



20

Lng \approx 28, Do \approx 15.5



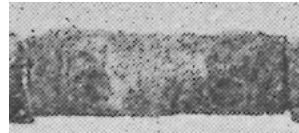
21

Lng \approx 56.5, Do \approx 15.3, Sct1 \approx 16, Sct2 \approx 36



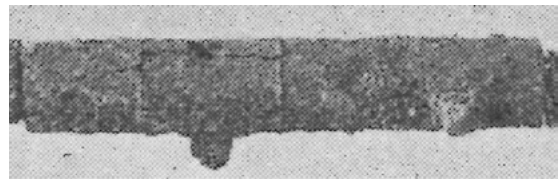
22

Lng \approx 42.2, Do \approx 14, H1Pos \approx 10.8, H1Dl \approx 5.5, H1Dt \approx 5, H2Pos \approx 32.6, H2Dl \approx 5.5, H2Dt \approx 5, H2Az=5



23

Lng \approx 78.3, Do \approx 14, H1Pos \approx 8, H1Dl \approx 5.3, H1Dt=5.4, H2Pos \approx 27.7, H2Dl \approx 5.1, H2BS=R, H2BPos=1, H2BAz \approx 120, H3BS=R, Sct1 \approx 18, Sct2 \approx 38.5



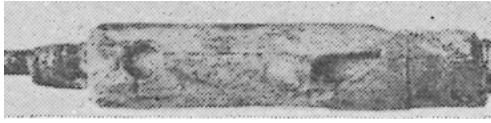
24

Lng \approx 23.5, Do \approx 11.2–15.8



25

Lng≈70, Do≈15, H1Pos≈10, H1Dl≈6, H2Pos≈43, H2S=T, H2Dl≈6, H2Dt=5, H2Az=10, H2DIT=12.5, Sct1≈57



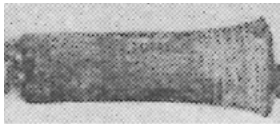
26

Lng≈40.5, Do≈10–14.5, Sp2L≈10.6, Sp2D≈9.8



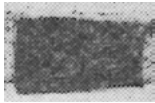
27

Lng≈40, Do≈15.5–11.5



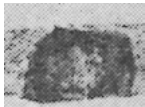
28

Lng≈21.5



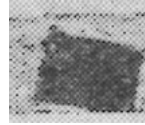
29

Lng≈20



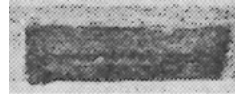
30

Lng≈12

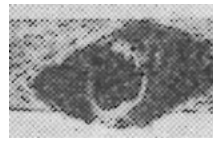


31

Lng≈33



32



33

Lng≈13



34

Lng≈11



9 Conclusion: A Tale of the Queen's Pipes

Stefan Hagel

Judging from his attire and demeanor, the man who entered Alexandria's finest woodwind workshop was of Greek descent. His name confirmed that, and intimated that he belonged to a family of musicians. So far, he would have been the typical customer. But it turned out that he had completed a long journey down the Nile Valley, from beyond the lands that were now firmly under Roman rule, since Cleopatra had taken the wrong side in the last big conflict, not so long ago. Being a highly trained piper, he had been lucky enough to associate with the court of the Candace of Ethiopia, serving the African state's demand for Mediterranean cultural imports. Consequently, he had been entrusted with the mission to procure a set of instruments worthy of royal ceremony. For such an endeavor, Alexandria was certainly the place to go, not only because it was comparatively easy to reach or because it offered the opportunities of the largest city of the known world. More importantly, Alexandria had been at the forefront of musical innovation for a while, with the invention of the hydraulic organ and novel gadgets for the doublepipe that added considerably to the musical capabilities of this traditional instrument, which the Greeks called the "aulos." After all, Cleopatra's father was still remembered by the older generation as the aulos-playing king.

Being deeply connected with Egypt through the Nile, Ethiopia was not really an exotic place. In the time of Homer, its kings had extended their rule over Egypt as well. The epics, familiar to any Greek schoolchild, remembered it as a land beloved by the Gods as well as the home of King Memnon, most beautiful of mortals and one of the heroes slain by Achilles in front of the gates of Troy. In the ages-old tradition of cultural exchange with Egypt, Ethiopia had been adopting more elements of Greek culture once its northern neighbor had been ruled by Greek-speaking pharaohs, after Alexander had upset the system of the world. Along banquets with wine and dance, the cult and imagery of Dionysus had gained importance, inevitably calling for accompaniment by the aulos as the god's prototypical instrument. Of course, no average aulos would suit the might and splendor of the proud new ruling queen Amanishakheto, least of all one of the cheap wooden models.

Auloi came in many types and sizes, suited for a great variety of music. They were all driven by double reeds with their exciting sounds reaching from deep buzzing to shrill treble notes. At any rate, to provide for all possible contexts, from royal processions to festive dancing, from parties to funerals, from sacrifices to accompanying the famous arias of Greek dramatists, many different instruments would be required. The basics were quickly explained, but, as always in such matters, the details had to be worked out according to the physical capabilities of the envisaged players as well as musical preferences:

"First of all, we need regular middle-sized pipes, right in the range of vocalists. They need not go much lower than a kithara but must be equipped with keywork down to that range, so we can freely select various positions for our hands."

"Just one pair? Which keys are you going to use most?"

"Not at all, you know the Southern penchant for pairs and symmetry. We will need two instruments of every type that will be seen in royal ceremonies. This gives us a little margin in the individual design, so you can make them with different specialties. Of course they need to play together in Lydian, but otherwise, one instrument could go more in the Phrygian direction, while the other should include the chromatic notes both in the upper and in the lower part."

"Right, but once you have the upper chromatic on one pipe, it will make a lot of sense to add also the Hypolydian chromatic note, a fourth below, on the other—anyway, you may want the same pitch also in Phrygian context."

"That seems perfect."

“Talking about chromatic: we can offer you an exciting new design. Here, by turning just a single section, it becomes possible to switch between two different thumbholes. One for your regular diatonic up to the ‘Dorian treble note.’ But with the other one, you get all the chromatic semitones, and the scale terminates a tone lower, resulting in the old Phrygian harmony. You know, the octave scale that is supposedly sounded by the planets when revolving around the earth.”

“What a clever trick, we will take that! But you will include some extra treble notes on the higher pipes, right?”

“Sure, up to the limit of the Perfect System. For good measure, we will also add its remaining three lowest notes on certain points.”

“Great! I’ve seen you also produce middle-sized pipes with additional bass holes? We would definitely like to try these as well.”

“Those with rectangular bass holes, whose pitches can be adjusted? Also two instruments?”

“Well, I don’t really know yet.... But let’s stay on the topic of the chromatic for a moment. We must be prepared for dirges, so we need something high-pitched in chromatic scales. Flurries of semitones lamenting deceased royalty....”

“If you also require two of that type, we can nicely stagger their scales, giving you lots of musical options. You are comfortable with overblown treble notes, in this case, aren’t you?”

“Of course we are—it would be next to impossible to finger the intervals directly!”

“That is not all, is it?”

“No, I’ve left the complex items for the end. Something for choral performances and so on, playing in the old seven modes, but of course cutting-edge, technology-wise. Not some naked bone auloi, as if we were still in the age of Alexander.”

“Are you trained with instruments of almost four foot length?”

“Would we be playing for the Candace, if we weren’t?”

“All right, if you want to go for the full program, we can make you a pair of instruments that will not only give you access to the seven modes but to all the respective bass notes as well. You’ll be able to preselect any of these, using rotary tubing, and we’ll also add our customary incised springs, so that the tubes won’t start moving from the vibration. You will still be able to modulate on the fly, because the instruments always allow you to switch to the Lydian and Phrygian bass notes from whatever else you are playing. To that end, we mount a single slider on each pipe. I know, it’s not three sliders like they used to make, but then, you couldn’t really manage these without interrupting the music. On our models, a finger is reserved for the slider, so you can jump right from one bass note to another.”

“I appreciate that, but with one fingerhole less, won’t it become difficult to access all required pitches?”

“That’s where our elevated fingerholes come into play: on the high pipes of each pair, we mount short inclined tubes over some outlets. On the one hand, this reduces the finger stretch and makes playing the intended notes much more comfortable, or indeed just feasible. On the other hand, they make it possible to produce two distinct pitches from a single hole with precision, depending on whether you keep the finger on the hole below or not. Even so, these remain formidably difficult instruments. The hands being held rather close to the mouth, the leverage of such long pipes is hefty, even though we strive to reduce the bronze walls to the absolute minimum—and as you know, the entire weight rests just on the tips of the thumbs.”

“Anyway, this seems to be just what we are looking for. How about the treble notes here?”

“If you like, we can tune the higher index hole to its traditional optimal position, but I don’t think the resulting stretch is for everybody. I presume you can inform us about the limits of the envisaged musicians?”

“Yes, I’ve brought templates that indicate the maximally achievable finger spans as well as the possible ranges for the fingers in between and where they would come to lie. I guess you can work from that?”

“Perfect. I’ll make some sketches and we can discuss all the details tomorrow.”

A couple of days later, the production chain sprang into action. First, suitable animal bones had to be selected to form the main bodies of the instruments, wherever absolute stability of form was required. Coming in usable lengths of only a few inches, they were drilled inside and turned outside, to perfect

cylinders that could be socketed together to long tubes. Slightly larger bones would form the decorative bulbs close to the mouth ends; largely remaining exposed to the view, these needed to be flawlessly white. For the simpler sections, olive wood was used instead—hard and stable, reasonably resistant against humidity if appropriately treated, but lighter than bone, and available in greater lengths and quantities. Then the furnaces were fired. Most metal parts would be formed from a bronze with moderate amounts of tin. Strictly controlled alloys, however, were only produced for crucial mechanical parts, while recycled material would suffice for simple tubing. Bronze tubes of various diameters first had to be cast, in lengths ranging from a couple of inches to more than a span. Afterwards, they were reamed inside and turned outside, once more producing perfect cylinders. The most highly qualified slaves were fabricating those that would be fitted within each other, so that an external layer could be rotated around the inner tube. Maintaining airtightness while keeping the parts movable, they worked to exacting standards that had been unheard of only a couple of generations ago. Others put the ends of some cylinders over mandrels and hammered them out to flares, which would either form decorative pipe exits or encase the sockets for the reed mouthpieces. Once fitted over wood or bone, their ends were skillfully bent over the edges, to hold the cores firmly in place. Some workers were busy preparing various forms of knobs to solder on the tubes, filing and drilling cast blanks in the form of triangles, rings, and globules. Meanwhile the designers had experimented with models, in order to determine the optimal parameters for the elevated fingerholes. According to their specifications, finely decorated side tubes were cast in different sizes, ready to be fastened over the respective toneholes. However, the casting team's most admirable feat were the sliders—not so much because of the finely molded seashells that went over the toneholes, or the tiny dolphins that held them in their snouts, but for the long thin rods that went halfway around the tube and were extremely tricky to cast, because the mold had to be heated almost to the temperature of the molten bronze. Their rectangular cross section was precisely matched by small bearings of bronze sheet that would keep them on the tubes. Friction between the bronze surfaces was cleverly reduced by tinning the undersides of the rods. Finally, there was the silversmith, who magically managed to plate the necks in the bone bulbs with a fine silver collar.

Many parts assumed their final shape only on assemblage. The instruments grew from the mouthpieces downward. Only when a new section was ready for mounting, did it become possible to mark the tonehole positions, drill them, layer by layer, and file them to shape—most elliptical, some rectangular, and a few in elegant teardrop-shaped curves that facilitated half-covering them. Where rotary sleeves were involved, a knob was soldered on sideways, using a fast-smelting alloy of tin and lead, before the sleeve was slipped over the internal tubing. Bone and wood cores were firmly socketed together, the connections being sealed with windings of flax, before being covered with another length of bronze encasing, sometimes connected to its neighbor by a thin ring soldered inside across the boundary. In other cases, the connections were even left unglued, so that the performers would remain able to turn the sections relative to each other for the most convenient fingerhole placement. Before adding another section, the intonation of the existing toneholes was checked by means of pitch pipes and, whenever necessary, corrected by enlarging them slightly, filing their internal edges round, or even adjusting the bore diameter. Error had to be kept to the lower side, though: it is not feasible to shrink a hole whose pitch has become too high. The sliders were mounted on long sections without holes, while sticking out at either end: in this way, the tonehole could be positioned beneath the seashell-shaped plate with utmost precision. The rods were kept aligned with the tube by running halfway around it at one point, while their movement was restrained to just the diameter of the tonehole by placing the bearings right at the edges where the rod bent around the pipe.

The finished instruments were polished to the bright golden hue of fresh bronze surfaces. As a last addition, colorful threads of finest hemp were passed through the holes in most of the knobs and wound around their tips. These would cushion the players' fingers from the edges of the metal when they would use them for turning the external cylinders to expose or close certain toneholes. The windings would of course wear off and need replacement; it would be a good idea to pack some spare thread with the products. Otherwise, maintenance would mostly include wiping and polishing the metal, as well as making sure that none of the rotary tubes would get stuck by corrosion that inevitably forms on wind instruments.



Figure 9.1: Meroë, North Cemetery.

Soon the entire set was shipped up the Nile, being temporarily unloaded at each cataract during the longer second part of the journey under an increasingly higher sun. At the royal city of Meroë, the instruments were finally handed over to the musicians, who needed to acquaint themselves with the various fingerhole positions and modal capabilities, adjust suitable reed mouthpieces, train their fingers to master the required spans and weights with sufficient ease, and finally to balance the two pipes of each instrument in perfect harmony.

In the years to come, their music accompanied most aspects of court life. The deep buzzing of the long tubes, the clear sound of the treble notes, the even shriller whistling of overblown pitches, combined as well as alternating, struck the listeners with due awe toward the gods as well as the semidivine rulers. Pleasant melodies, unfolding in concords and discords, sometimes resolved to unison, added to the luxury of royal banquets, often accompanying choruses of dancers. The music invoked the spirit of Dionysus, promising forgetfulness of all evils, and bliss that extended to the next realm—as if the god, after leaving Alexandria when, as it was told, forsaking Cleopatra’s hapless last consort, had settled in Meroë as the last independent Empire on the Nile.

Fittingly, the instruments reached their final purpose in the funeral of the queen who had ordered them. Not all of them were deemed appropriate for such an occasion, however: some with particularly joyful associations were left behind in the city. The others alternated in the funerary procession, playing in symmetrical pairs, slowly moving toward the royal cemetery, whose pointed pyramids overlooked the scorched plains. When the Candace had been laid to rest in her subterranean burial chamber, among jewels and splendid offerings, and the doors had been sealed, the auloi would sound for a last time during the funerary banquet, celebrating her fame and her transition to the divine sphere. Then they were silenced forever. Brutally bent and broken into pieces, they were deposited at the bottom of the stairwell that led down to the tomb and was about to be filled with soil: there the power of their music would still guard the deceased.



Figure 9.2: Reconstructions of instruments S1 and W2 by Marco Sciascia. Design and photograph: Stefan Hagel.

Two millennia passed. Wooden cores shrunk and crumbled. Water permeated the soil, encrusting certain spots with soluble minerals, and advancing colorful copper corrosion. Most soldered parts eventually became loose, as did joints between sections when the glue vanished. And yet, the African earth would prove a safer place than the world of the living. Buried deep underfoot and outside the grave chamber, the instruments even survived unnoticed when the Italian explorer Giuseppe Ferlini, in search of Meroë's fabled treasures, had the pyramid ruthlessly torn down in 1835. The first fragments to see the sun again were instead from the auloi that had remained in service in the city, when the pioneering archaeologist John Garstang retrieved them shortly before World War I. Being sent to his University in Liverpool, the few disjointed remnants of several pipes were exhibited on a wooden rack but disappeared, perhaps in the turmoil of World War II.

The formally buried instruments fared better. They were revealed during a joint expedition of Harvard University and the Boston Museum of Fine Arts, directed by George Andrew Reisner. When excavating the narrow stairwell in the early spring of 1921, a team of Nubian workers uncovered an array of cylinders of bone and metal, embedded in rubble and splinters. The excavation was immediately halted. Given its precarious state, it took more than a day to retrieve the unlikely find, duly photographed, from its location. The excavators identified the instruments as Greek-style auloi, even guessed their number correctly, packed the bits and pieces into crates, and shipped them across the Atlantic to the Museum of Fine Arts. As a heap of dirty and crumbling fragments, they never made it to the galleries there, despite arguably forming the most important music-archaeological discovery west of China. On the upside, this neglect preserved the find from misguided repair treatment, keeping it in a pristine condition that would later facilitate scientific investigation. The pieces passed through unknown hands, who muddled what little evidence the boxes had preserved from the original location of each piece, moving them around and occasionally joining unrelated items without documenting the changes. While completing an inventory of the museum's huge collection of musical instruments, Nicolas Bodley eventually described and published the find in 1946 but despaired about reconstructing even parts of the original instruments from the many dozen small tubes, let alone the myriad bronze chips.

Almost a century after their discovery, finally it was realized what an impact a better understanding of the find might have not only for music archaeology, but for Nubian studies, Egyptology, classical studies, and music history more generally. Funding was secured for a project that first allowed conservator Susanne Gänsicke to recreate the original sections as far as possible. The pieces were x-rayed, allowed to move from their dusty crates into neat new trays, and were subjected to various sorts of material analyses. Eventually the museum invited a team of experts from overseas for further interpretation. Unexpectedly, this process would take almost nine years, in which the researchers needed to develop novel methodologies, write dedicated software, let go of some deeply ingrained prejudices, measure, re-measure, and check the measurements, tell certain from doubtful connections, strain their eyes for tell-tale corrosion patterns, search for the pieces on the stupendous black-and-white photographs from 1921, feed databases, and predict and test possible musical scales with the help of the computer, eventually converting the hypotheses into playable models using 3D printing technology.

In the end, all sizable fragments had once again come together into meaningful musical designs, in what could be hoped to come close to their original order. And while an artisan started to reproduce replicas in bone, wood, bronze, and silver, the researchers had finally become able, with due caution, to tell a tale of the Queen's pipes.

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